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MTMC REPORT TE 73-44

MANUAL PROCEDURES FOR ESTIMATING

MARINE TERMINAL THROUGHPUT

PART ONE OF TWO
REVIEW, DERIVATIONS, AND PROCEDURES

MARCH 1978

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MILITARY TRAFFIC MANAGEMENT COMMAND

TRANSPORTATION ENGINEERING AGENCY

NEWPORT NEWS, VIRGINIA 23606

AUTHENTICATION

This report was developed in response to a need for more precise methodology in determining throughput capability at marine terminals. A series of formulas has been developed to measure the capability of physical facilities, personnel, and materials-handling equipment. These formulas have been integrated into methodology which uses a "weak link" approach. Here each subsystem of a port is analyzed separately and the capability of the weakest subsystem establishes the throughput capability for the port. Examples are included with detailed calculations for different types of terminal operations, such as breakbulk, container, RORO, and barge ship.

We look forward to the future when the use of this tool will refine and validate the techniques and concepts which have gone into its development.

ALLEN J. DOWD
Special Assistant for
Transportation Engineering
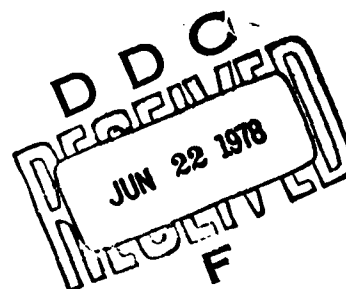
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MANUAL PROCEDURES FOR ESTIMATING MARINE TERMINAL THROUGHPUT.

PART ONE OF TWO 1.

REVIEW, DERIVATIONS, AND PROCEDURES.

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EXECUTIVE SUMMARY

The Military Traffic Management Command Transportation Engineering Agency (MTMCTEA), Newport News, Virginia, developed a methodology for determining and predicting the cargo throughput capability of marine terminals, as directed by Headquarters, MTMC[1], in response to a request by Commander in Chief, US Army, Europe.[2] This methodology systematizes the input factors and organizes them into mathematical expressions with which one can manually calculate cargo throughput rates. The methodology enabled planners and engineers to estimate marine terminal capability for four types of cargo: break-bulk, containerized, roll-on/roll-off (RORO), and LASH/SEABEE barge. The procedure used for estimating capability is the weak-link analysis, in which each basic subsystem in a port is analyzed separately to determine its cargo throughput capability. The subsystem having the least capability is the weak link, and the output of the port system as a whole can be no greater than that of this weak link. Example problems are shown, with detailed calculations, for marine terminal operations with the four different types of cargo mentioned above. Also, an example is shown wherein analysis is made of combined operations. The developed procedure is applicable for cargo-throughput analysis either for loading ships in CONUS or for unloading ships at oversea ports. However, the special restrictions involving ammunition shipments were not specifically addressed by this study, but the developed procedure is applicable for ammunition shipments if a constraint due to special restrictions is treated as a weak link. This methodology has not been validated by an actual test in an operating port environment.

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[1] Reference: Letter, MTMTS-SA, 14 February 1973, subject: Methodology for Estimating Port Throughput Capability.

[2] Reference: TWX, ECJD-T, HQ CINCUSAREUR, 24 0845Z January 1973, subject: Seaport Capability Study (U).

I. SCOPE

This methodology is intended to provide planning personnel who have port movement responsibilities with an understanding of the many factors involved and their relationship to each other. It also provides a technique for manual evaluation of marine terminal throughput capability, given basic demands. The technique is applicable for both onloading and offloading ship cargo. The study measures and incorporates:

A.   Capabilities of various types of equipment and methods for handling cargo

B.   Cargo throughput for different types of ships, such as break-bulk, container, barge-ship, and roll-on/roll-off

C.   The effect on the cargo throughput of holding-area size

D.   The effect of factors such as weather and visibility on productivity

Transfers between inland or intracoastal water modes and oceangoing vessels are not included with the exception of the LASH and SEABEE barge-ship systems. Excluding bulk cargo (dry or liquid), any commodity used to support military operations overseas is within the scope of this study. Passenger movements are not covered. Special requirements attributable to ammunition shipments are not considered in this report.

II. OBJECTIVE

The methodology developed in this study provides planners and engineers of the distribution system with a capability measuring procedure for marine terminals; this is done by including and quantifying those factors which affect the capability of a terminal to transship cargo. This methodology is designed to systematize input factors and their organization into mathematical expressions capable of providing the facility under consideration with valid throughput capability values.

III. INTRODUCTION

Terminals, as considered in this report, are those facilities that transship cargo between land transportation modes and oceangoing vessels. The primary function of a terminal is the transshipment of cargo, although subordinate functions may include cargo consolidation, distribution, and storage. Capabilities in all marine terminal functions are dependent upon facilities, labor, equipment, and management, with the latter exerting a strong influence. Six principal operations describe the general procedures in a marine terminal:

1. Vessel approach and berthing

2. Cargo transfer between vessel and shore

3. Cargo special handling (for example, customs, warehousing)

4. In-transit storage

5. Cargo transfer to and from land modes

6. In and out processing of inland mode vehicles

The manner in which these operations are performed provides the basic input for determination of marine terminal capability.

In its broadest sense, marine terminal capability is a measure of the ability to provide the six basic port functions when available resources are origanized in the most effective manner. Many types of capability measurement are possible, including nonquantifiable measures of performance. One common measure of capability is the gross cargo transshipped per unit of time, such as short tons per year. Although commonly used, it is a measure that ignores much available basic information concerning individual functions. For example, transfer of 10,000 short tons per day of iron ore does not have the same meaning as does transfer of 10,000 short tons per day of 2-1/2-ton trucks, since there are obvious differences in the kinds of resources needed to move each type of cargo.

If specific estimates of marine terminal capability are desired, those estimates will apply only to a very narrow set of conditions, and those conditions may not all be measurable. Our aim, then, was to produce a methodology for marine terminal capability estimates that would yield more useful information than gross statistics, yet would not be limited to specific situations. The resultant methodology, as described in this

report, gives estimates of capability that can be used to identify major differences between ports for four kinds of cargo: general (break-bulk), containerized, unit equipment, and LASH/SEABEE barge. The procedure used to estimate capability is the weak-link analysis.

An exhaustive search of literature was conducted at both the Fort Eustis Transportation School Library and the Army Air Mobility Research and Development Laboratory Library. Information was requested from the United States Maritime Administration and the American Association of Port Authorities. Dr. Joseph D. Carrabino[3] and Dr. Ernst Frankel[4], both of whom are considered leaders in the field of port cargo throughput, also were contacted concerning latest developments in the field.

Part One of this report is in two principal sections. One section reviews some existing methods for estimating port capability. The other section presents the procedures developed in this study to estimate port throughput for both loading cargo into and unloading cargo from the ship. The derivations of the equations and techniques are shown, and numerical examples are furnished, to illustrate application of the methods.

A reference guide, or pamphlet, published as Part Two, provides a condensation of procedure from the main report for estimating marine terminal capability[5]. Data on vessel characteristics are included in appendix B to Part One of this report because the required holding area is a function of vessel capacity.

Another report[6] that resulted from work on this project contains descriptions of the different types of cargo vessels in use; it describes typical port operations associated with the vessels. For the convenience of the user, an appendix, "Ship Loading Factors," taken from MTMTS Pamphlet 700-1, is included.

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[3] Dr. Joseph D. Carrabino, Chairman, Engineering and Management Sciences Corporation.

[4] Dr. Ernst Frankel, Professor, Department of Ocean Engineering, Massachusetts Institute of Technology.

[5] "Condensed Procedures." Manual Procedures for Estimating Marine Terminal Throughput, Part Two.

[6] Marine Terminal Operations, Military Traffic Management Command Transportation Engineering Agency, Newport News, VA, 1977.

IV. EXISTING METHODS FOR ESTIMATING PORT THROUGHPUT

A. GENERAL

Previously developed techniques for general (break-bulk) operations rely upon berth design and occupancy factors. For container operations, attention has been placed upon mathematical simulations used as a design aid. Other work has been undertaken to determine operating procedures or investments at a port, or system of ports, that will provide for cargo flow in an efficient, economic manner. Selected references are contained in the bibliography. Several of the more important techniques in use are presented in this section.

B. FACTOR METHODS

1. Military

The military factor method was developed prior to World War II and was used successfully during the war. It was updated by a working group in 1955.[7]

This method involves determination of wharfage suitable for discharge of military general cargo. For each linear foot of such wharfage it assumes that 1 long ton of mixed general cargo can be discharged in 1 day of 20 effective working hours. For example, a suitable wharf, 1,200 feet in length, would be considered to have an unloading capacity of 1,200 long tons per day. While assessments so made are for a 1-day period, this does not imply that the estimated rates cannot be sustained day after day. It does indicate, however, that a sustained rate must also be predicated on the capability of port clearance facilities.

The working group concluded in 1955 that the 1-ton factor should be increased to 1.2 tons, due primarily to increased mechanical efficiency of break-bulk-type ship-handling gear. The values produced by this formula are applicable to unloading operations only; the ability of the port to clear the cargo must be analyzed separately to see if it is a restriction. The types of berths to which this factor may be applied are shown in the following tabulation:

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[7] Port Capacity Methodologies, US Army Transportation Intelligence Agency, Ports and Harbors Branch, Washington, DC, 1955.

<div align="center">Berth Dimensions</div>

Length (ft)	Depth (ft)	Ship Type
565	31 to 30	C4, C3
460	29 to 23	VC2, EC2, C2, C1-B
350	22 to 18	C1-M

For general planning purposes, a transportation terminal service company is considered capable of discharging from the ship 720 short tons per 20-hour working day.[8] The average ship is considered to be 500 feet long and 60 feet wide with five hatches. Of course, the disadvantage of this factor is that consideration is given only to the unloading operation at the berth. A checklist for terminal capacity estimation is given but no guide for the actual calculation of the factor is offered.

b. **Commercial**

Another simple factor method used by individual ports is to derive a capacity per unit of berthing space. Total general-cargo tonnage moved per year is divided by total general-cargo berth length to produce the factor. Using historical data from nine major Atlantic Coast ports, a Massachusetts Institute of Technology (MIT) study[9] revealed values ranging from a low of 9.5 STON/foot/year at Portland, Maine, to 247.6 STON/foot/year at New Haven, Connecticut. The average of 80.8 STON/foot/year was similar to the rate of 81.8 STON/foot/year achieved at New York harbor. These figures are presented simply to show the wide range of throughput at different ports.

Generally assumed capacity measures for general-cargo berths are used also. The most common assumes that 150,000 STON per year can be handled at a 550-foot marginal berth without dockside cranes. If efficient shore cranes are available, a formula for berth capacities, in STON/year, is as follows:[10]

$$\text{Capacity} = 250,000 + 500 \,(\text{length in feet} - 550 \text{ ft})$$

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[8] FM 55-15, Transportation Reference Data, Department of the Army Field Manual, February 1968, pp 5-48 to 5-90.

[9] Frankel, Ernst, Studies on the Future of Atlantic Ports, Report MITSG 72-18, July 10, 1973, p 82.

[10] Ibid., p 106.

C. IDEAL BERTH METHOD

A procedure was developed in 1965 for estimating port capacity using the concept of an ideal berth. [11/] The ideal berth was defined as one that is ideal in all components; that is, apron strength, apron width, heavy-lift capability, transit shed size and arrangement, open storage area, backup warehousing, rail and highway access, ease of berthing, and so forth, and, by definition, was capable of handling maximum cargo of 100,000 STON per year. A berth would be scored based on the criteria in Table I, with an ideal berth scoring 1,500 points. Berth capacity is, then, the actual score divided by 1,500, and multiplied by 100,000 STON per year.

D. MTMC PLANNING FACTORS

The experience of the Military Traffic Management Command, which is responsible for scheduling, routing, and loading all Department of Defense material being transported overseas via ocean shipping, has led to development of actual and notional factors to estimate ship-loading times. These values are a refinement of the planning techniques used previously, such as the factor methods, in that the different types of shipping methods and cargo are treated separately. Appendix C of MTMTS Pamphlet 700-1, which gives these factors, is reproduced herein as Appendix A. Port capacity can be determined by first calculating the types of ships that can be berthed in a port, then applying the appropriate factors for the cargo and ship types; capacity is the estimated amount of cargo that can be loaded in a given time.

E. QUEUING THEORY METHOD

Port capacity estimates are based upon the queuing theory, where a port is a server meeting the demands imposed by customers; in this case, the customers are the vessels that arrive in a random sequence. Central to this theory is the assumption that, although the arrivals are random, the probability distribution of the times between ship arrivals can be reasonably approximated by a known probability distribution function. A parallel assumption is that the time spent processing a ship is also random but that it also can be approximated by a probability distribution function.

11/Eschback, A. M., Ideal Berth Measurement of Port Capacity, Proceedings of the Fifty-fourth Annual Meeting, American Association of Port Authorities, Oct 11-14, 1965, pp 37-40.

TABLE I

IDEAL BERTH FACTORS

	Points
Berth Length (feet)	
750	120
700	100
600	80
500	50
< 500	10
Water Depth (feet)	
40	90
35	80
32	60
30	40
< 30	20
Back Up Area (sq feet)	
400,000	120
300,000	80
200,000	50
100,000	20
< 100,000	10
Apron Width (feet)	
60	110
40	90
20	40
< 20	10
Transit Shed (sq feet)	
90,000	120
50,000	60
< 50,000	20
Distribution Shed (sq feet)	
30,000	90
20,000	60
< 20,000	20
Apron Tracks	
2 tracks	100
1 track	50

TABLE I - cont

Deck Loading (lbs/sq feet)
    800   100
    600   80
    500   50
  < 500   10

Heavy Lift Cranes
    1 - 35-ton straight-line   110
    2 - 65-ton Whirley   90
    2 - 50-ton Whirley   80
    2 - 35-ton Whirley   70
    1 - 65-ton Whirley   70
    1 - 50-ton Whirley   50
    1 - 35-ton Whirley   30

Berth
    Quay or marginal   110
    Slip   20

Truck Tailgate
    Full length of house   90
    At end of house   40

Loop R.R. Tracks
    Yes   60
    No   0

Truck Access
    Direct to freeway   120
    Direct to state highway   100
    Direct to city arterial   80
    Direct to city street   50

Ship Service Facilities
    Power, water, & sewer   60
    Power & water   30
    Water only   10

Conditional Age of Facility
    Condition of structures determines
        effectiveness.
    Reduces or increases effectiveness
        of other factors by maintenance.
    New   100
    25 years old   50
  < 50 years old   0

Solution of the problem requires knowledge of the probability function for the times between ship arrivals, the probability function for ship service times, and the number of servers, or berths. In most cases, queuing theory assumes that the probability functions are related to the Poisson theory; each arrival is assumed to be an independent event and the occurrence of one event has no bearing upon the occurrence of another. A good discussion of the theoretical basis for these models appears in Appendix B of Studies on the Future of Atlantic Ports by Ernst Frankel.

Using historical data for a port, an appropriate method is selected that will approximate the real information. Inherent characteristics of the theories permit inferences to be made about expected berth occupancy rates, times between ship arrivals, and ship service times, and amounts of cargo to be loaded on a vessel. By extension, these values indicate what the upper limits of port capacity will be. These methods have been used quite extensively in studies of liquid and dry bulk terminals.

F. COMPUTER SIMULATION

Evaluations of a complex system, such as a port, often require information that is beyond the limits of even very complicated analytical methods to supply. When direct solutions are not feasible, it is possible to move toward the solution by studying how the system operates in different configurations. Computer simulation is such a technique. By describing the system with mathematical formulae, especially by using probability distribution functions to describe elements which behave in a random fashion, a researcher can "build" a representation of the system in the computer. By studying how the system performs in various configurations, operations can be observed without having to make physical changes to the real system.

Simulation has been used most often to study container facilities. Important design considerations are the amounts of container storage, the number of major equipment items (for example, container cranes and handlers), the number of entry gates, and the size of the container freight station. Ship arrivals are usually approximated by probability distribution functions of the Poisson type. Decisions about port layout are made from information from the simulation program such as operating costs, delay times for cargo moving through the port, equipment utilization rates, and amounts of storage demanded.

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G. SUMMARY

Techniques presently in use for estimating port capacity are of three kinds:

1. Estimates based on berth size or length. These are limited primarily by consideration of the transfer rate from wharf to vessel; it is implicitly assumed that the backup facilities will be adequate.

2. Reliance upon past performance. These indirectly take in the way the whole system operates, but they are not necessarily a valid guide toward the upper limits of productivity.

3. Simulation and queuing theory. This provides a method for examining the system as a whole.

The expense in time and computer resources have limited their application, so far, to situations in which the information sought was economic in nature. Table II summarizes the various techniques that can be used for rule of thumb type calculations. Note that, with the exception of the ideal berth method, these methods apply only to the rate of output at the berth. Since none of these techniques wholly satisfies the objectives of this study, the method outlined in the following sections has been developed.

TABLE II
EXISTING METHODS FOR CALCULATING PORT CAPACITY

Method	Equation	Variable	Port Capacity*
Factor	(1.2 LTON/day/foot) (L, feet)	L - feet Berth length	LTON per day
MIT Study New Haven, CT	(247.6 STON/year/foot) (L, feet)	L - feet Berth length	STON per year
MIT Study Without Dockside Cranes	150,000 STON/year for 550-foot berth		STON per year
MIT Study With Dockside Cranes	250,000 + 500 (L, feet - 550) STON/year	L - feet Berth length	STON per year
Ideal Berth	$(P, points) \dfrac{100,000 \text{ STON/year}}{(1,500 \text{ points})}$	P - points (see Table I)	STON per year
MTMC Planning	C - ship capacity in MTON T - loading time in days	C, T (Appendix B)	MTON per day
FM 55-15	720 STON per 20-hour day		STON per day

*Find variable and use factor to calculate port capacity.

V. PROCEDURE FOR ESTIMATING PORT THROUGHPUT

A. BASIC ASSUMPTIONS

1. The required ships are available.

2. The range of effect of each operational environment or constraint is identifiable.

3. Personnel to operate and manage materials-handling equipment (MHE) and port equipment are available in sufficient numbers to accomplish each operation at maximum equipment capability.

4. Operational constraints other than those concerned with equipment in port facilities will not be considered (that is, ship damage from mines, and so forth).

5. Holding space is used only for in-transit holding with no long-term storage.

6. To maximize throughput, ships to be loaded will arrive empty after discharging their cargo of containers or barges elsewhere.

7. There is unlimited cargo for input to the CONUS port and unlimited capacity for acceptance of cargo from the oversea port.

B. WEAK-LINK ANALYSIS

1. Description

The procedure developed in this study for estimating port through-put uses a weak-link analysis. Weak-link analysis is a technique for determining maximum cargo throughput by separate calculation of the capacity of each and every subsystem. These values are then compared with one another, and the minimum is the bottle-neck which limits all other subsystems. That is, the maximum cargo throughput of the port is limited to the value of the weakest subsystem, referred to as the weak link. The port system, as a whole, cannot transship at a rate greater than that of the weak link.

A schematic of operations for a typical terminal and the nomen-clature for the weak-link analysis is shown in Figure 1. The letters A, B, C, D, E, and F denote cargo movements from one

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┌──────────────┐    ┌──────────────┐    ┌──────────────────┐    ┌──────────────┐
│ OUTSIDE THE  │ A  │  INSIDE THE  │ B  │ CLASSIFICATION & │ C  │  IN-TRANSIT  │ D
│    GATE      │───▶│    GATE      │───▶│   DISPOSITION    │───▶│   HOLDING    │──┐
│              │    │              │    │      YARD         │    │              │  │
└──────────────┘    └──────────────┘    └──────────────────┘    └──────────────┘  │
                                                                                   │
   ┌───────────────────────────────────────────────────────────────────────────┘
   │
   │   ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
   └──▶│   STAGING    │ E  │              │ F  │              │
       │    AREA      │───▶│    WHARF     │───▶│    SHIP      │
       │              │    │              │    │              │
       └──────────────┘    └──────────────┘    └──────────────┘
```

LOADING

```
┌──────────────┐    ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
│              │ F  │              │ E  │   STAGING    │ D  │  IN-TRANSIT  │ C
│    SHIP      │───▶│    WHARF     │───▶│    AREA      │───▶│   HOLDING    │──┐
│              │    │              │    │              │    │              │  │
└──────────────┘    └──────────────┘    └──────────────┘    └──────────────┘  │
                                                                               │
   ┌───────────────────────────────────────────────────────────────────────┘
   │
   │   ┌──────────────────┐    ┌──────────────┐    ┌──────────────┐
   └──▶│ CLASSIFICATION   │ B  │  INSIDE THE  │ A  │ OUTSIDE THE  │
       │ & DISPOSITION    │───▶│    GATE      │───▶│    GATE      │
       │      YARD         │    │              │    │              │
       └──────────────────┘    └──────────────┘    └──────────────┘
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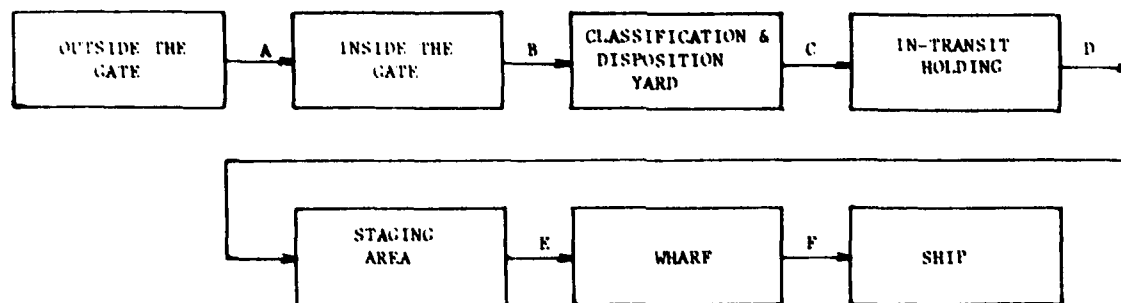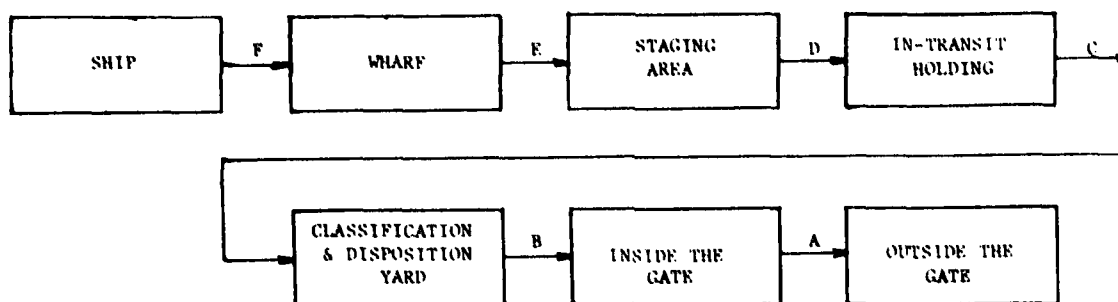
UNLOADING

NOTE: In a given operation, some subsystems may not be required or used, and they are omitted.

Figure 1.   Format for Weak-Link Analysis.

place to another, whereas the blocks shown on the figure represent
specific places at the port where cargo is usually placed for a
short time between movements.   For example, the letter "C"
denotes cargo movement from the classification and disposition
yard to in-transit holding.   The calculations shown on the follow-
ing pages use the format of Figure 1 to identify the cargo move-
ments A, B, C, D, E, and F.   The weak link is identified by
comparing the results of the calculations for the cargo movements
and also for the required size of the in-transit holding area.   An
example will be presented in a later section, with calculations
showing the complete cargo movement path from the entrance gate
to the ship for a one-berth containership port.

Note that the same technique is used for both loading and unloading the ship. This feature is made possible by the manner in which the equations are set up. The terms in the equations, which are filled in by the operator, are defined as rates. These equations are applicable for either loading or unloading. The equations simply denote movement of cargo from one point to another; the operator, who is the only one with the knowledge of the actual rate, supplies the rate to fit the appropriate case. That is, in the case of the cargo throughput calculation at the break-bulk berth, the stevedoring rate is one of the values to be supplied by the operator. So, the applicable rate for loading or unloading is used.

Also, in the case of a container berth, the only rate used in the equation is the crane cycle rate, which is the same for loading or unloading. Therefore, the equations are flexible in that the same equation fits either case, loading or unloading, simply by using the applicable rate.

As an alternative, if the port operator cannot apply the mathematics required to calculate the output of each subsystem, Figure 1 can be used as a guide to identify the weak link. An estimate, based on experience, can be made for each subsystem; then, by comparing subsystem outputs, the weak link is identified. The throughput of the weak link is, of course, also the maximum throughput of the terminal. This method is not advocated, but is offered simply as an alternate method, or as a second-best approach. This approach would stimulate consideration of subsystem output values. Consideration of berth output only, instead of the capacity of the backup systems, is a common mistake among port operators.

2. Calculations for Weak-Link Analysis

The letters A, B, C, D, E, and F, shown in Figure 1, are used in the nomenclature of the following equations. Derivation of the equations used to calculate a rate of cargo movement is based on counting the number of loads or the number of vehicles in a measured interval of time. The cargo movement rate is derived also by calculating the round-trip time for a vehicle, based on the physical characteristics of the system. Then, knowing the number of vehicles, the tonnage carried by each vehicle, and the number of hours worked, the cargo movement rate can be calculated. The equations are derived with the port's throughput expressed in MTON per month. This unit of measure is considered to be widely acceptable for comparing one port's output

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with another. However, if this unit is not desirable, an engineer or planner using this report can easily use dimensional analysis to change the equations to a desired unit. For example, the preference could be to express the output of a RORO berth in number of vehicles *per month* instead of MTON per month. Of course, to convert from one unit to another, the cargo densities must be known, but for military moves the average cargo mix is well known. The following terms are defined for use in the equations:

S = Number of shift hours per day worked for a particular movement

N_1 = Number of locomotives available for a particular movement

N_2 = Number of railcars per train for a particular movement

d = One-way distance in feet that a vehicle travels for a particular movement

V = Average velocity of a vehicle in miles per hour, not including time spent at end points, based on observed values with the level of activity that is to be gauged, or may be estimated, based on experience

H_1 = Pickup time in hours for the vehicle to pick up the load at the beginning of a movement

H_2 = Dropoff time in hours for the vehicle to drop off the load at the end of a movement

H = $\dfrac{2d}{5280V} + H_1 + H_2$, round-trip time in hours for a vehicle

to move cargo, including pickup and dropoff times

W = $1 - W_1$, where W is defined as the weather factor and W_1 is defined as the fraction of total time lost to severe or inclement weather. The weather factor degrades the throughput capability to account for the effects of adverse weather. (Note that $W_1 < 1$, necessarily, and that the values may vary for different types of operations. For example, rain may not affect container loading but would affect break-bulk loading.)

$$G = \frac{P_1 + 0.75 P_2}{P_1 + P_2} \text{ for 25 percent nighttime degradation rate,}$$

where G is defined as the night productivity factor that accounts for the effect of reduced visibility. P_1 is defined as the number of shift hours worked in daylight and P_2 is defined as the number of shift hours worked at night.

$L = 1 - L_1$ where L is defined as the shift-change factor that accounts for the time loss due to changing work shifts, including meal breaks, and L_1 is defined as the fraction of total time loss due to shift changes, including meal breaks.

$s = 1 - s_1$ where s is defined as the dredging factor and s_1 is defined as the fraction of total time loss due to dredging. This factor will be used only if a yearly estimate of berth throughput is needed, since the factor cannot be realistically applied to a monthly figure because dredging is not done every month, and since applying the factor would change the number of ships per month and the ship cycle time. Actually, the berth would operate month after month, unaffected by dredging, and then cease operations completely while the berth was being dredged. The annual berth output is 12 times s times the monthly berth output.

NOTE: these terms will have various subscripts in the following paragraphs, according to the nomenclature of Figure 1 and the mode of movement, such as rail-R, truck-v, and so forth.

    a.   Cargo movement A, from outside the gate to inside the gate (vice versa for unloading ships overseas).

        (1) Rail

            A_R = Input rate by rail in measurement tons per day

            n_{AR} = Number of railcars that can be moved to inside the gate per day

            N_3 = Number of trains per day that can be received at the gate

N_2 = Number of railcars per train

n_{AR} = $N_2 N_3$

M_R = Load capacity of railcar in number of measurement tons

A_R = $n_{AR} M_R$ W G L

(2) Truck

A_v = Input rate by truck in measurement tons per day

t_A = Number of hours per truck, amount of time for one truck to make movement A

n_{Av} = Number of trucks that can be moved to inside the gate per day

n_{Av} = $\dfrac{S}{t_A}$

M_v = Number of measurement tons per truck

A_v = $n_{Av} M_v$ W G L

(3) Total cargo movement A

A = Total rate of input to the port by rail and truck in measurement tons per month

A = $30 (A_R + A_v)$

b. Cargo movement B, from inside the gate to classification and disposition yard.

(1) Rail

B_R = Movement rate to classification and disposition yard by rail in measurement tons per day

n_{BR} = Number of railcar loads that can be moved to classification and disposition yard per day

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$$H_{BR} = \frac{2\,d_{BR}}{5280\,V_{BR}} + H_{1BR} + H_{2BR}$$

$$n_{BR} = \frac{N_{1B}N_{2B}\,S}{H_{BR}}$$

M_R = Number of measurement tons per railcar

$B_R = n_{BR}\,M_R\,W\,G\,L$

(2) Truck

B_v = Movement rate to classification and disposition yard by truck in measurement tons per day

n_{Bv} = Number of truckloads that can be moved to classification and disposition yard per day

$$H_{Bv} = \frac{2\,d_{Bv}}{5280\,V_{Bv}} + H_{1Bv} + H_{2Bv}$$

N_{Bv} = Number of trucks available for movement B

$$n_{Bv} = \frac{N_{Bv}\,S}{H_{Bv}}$$

M_v = Number of measurement tons per truck

$B_v = n_{Bv}\,M_v\,W\,G\,L$

(3) Total cargo movement B

B = Total rate of movement to classification and disposition yard by rail and truck in measurement tons per month

$B = 30\,(B_R + B_v)$

c. Cargo movement C, from classification and disposition yard to in-transit holding area.

(1) Rail

C_R = Movement rate to holding area by rail, in measurement tons per day

n_{CR} = Number of railcar loads that can be moved to holding area per day

$$H_{CR} = \frac{2\, d_{CR}}{5280\, V_{CR}} + H_{1CR} + H_{2CR}$$

$$n_{CR} = \frac{N_{1C}\, N_{2C}\, S}{H_{CR}}$$

M_R = Number of measurement tons per railcar

C_R = $n_{CR}\, M_R\, W\, G\, L$

(2) Truck

C_v = Movement rate to holding area by truck in measurement tons per day

n_{Cv} = Number of truckloads that can be moved to the holding area per day

$$H_{Cv} = \frac{2\, d_{Cv}}{5280\, V_{Cv}} + H_{1Cv} + H_{2Cv}$$

N_{Cv} = Number of trucks available for movement C

$$n_{Cv} = \frac{N_{Cv}\, S}{H_{Cv}}$$

M_v = Number of measurement tons per truck

C_v = $n_{Cv}\, M_v\, W\, G\, L$

(3) Straddle carrier

C_s = Movement rate to holding area by straddle carriers, in measurement tons per day

n_{Cs} = Number of straddle-carrier loads that can be moved to holding per hour

$$H_{Cs} = \frac{2\, d_{Cs}}{5280\, V_{Cs}} + H_{1Cs} + H_{2Cs}$$

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N_{Cs} - Number of straddle carriers available for movement C

$$n_{Cs} = \frac{N_{Cs}\, S}{H_{Cs}}$$

M_s - Number of measurement tons per straddle carrier

$$C_s = n_{Cs}\, M_s\ W\ G\ L$$

(4) Total cargo movement C

C = Total rate of movement to holding by rail, truck, and straddle carrier, in measurement tons per month

$$C = 30\,(C_r + C_v + C_s)$$

d. Cargo movement D, from in-transit holding to staging area. (This segment may not be necessary in some cases.)

(1) Rail

D_R = Movement rate from holding to staging area by rail in measurement tons per day

n_{DR} = Number of railcar loads that can be moved to staging area per day

$$H_{DR} = \frac{2\,d_{DR}}{5280\ V_{DR}} + H_{1DR} + H_{2DR}$$

$$n_{DR} = \frac{N_{1D}\, N_{2D}\, S}{H_{DR}}$$

M_R - Number of measurement tons per railcar

$$D_R = n_{DR}\, M_R\ W\ G\ L$$

(2) Truck

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D_v = Movement rate from holding to staging area by truck in measurement tons per day

n_{Dv} = Number of truckloads that can be moved to staging area per day

$$H_{Dv} = \frac{2\ d_{Dv}}{5280\ V_{Dv}} + H_{1Dv} + H_{2Dv}$$

N_{Dv} = Number of trucks available for movement C

$$n_{Dv} = \frac{N_{Dv}\ S}{H_{Dv}}$$

M_v = Number of measurement tons per truck

$D_v = n_{Dv}\ M_v\ W\ G\ L$

(3) **Straddle carrier**

D_s = Movement rate from holding to staging area by straddle carrier in measurement tons per day

n_{Ds} = Number of straddle-carrier loads that can be moved to staging area per day

$$H_{Ds} = \frac{2\ d_{Ds}}{5280\ V_{Ds}} + H_{1Ds} + H_{2Ds}$$

N_{Ds} = Number of straddle carriers

$$n_{Ds} = \frac{N_{Ds}\ S}{H_{Ds}}$$

M_s = Number of measurement tons per straddle carrier

$D_s = n_{Ds}\ M_s\ W\ G\ L$

(4) **Forklift truck**

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D_f = Movement rate from holding to staging area by forklift truck in measurement tons per day

n_{Df} = Number of forklift truckloads that can be moved to staging area per day

$$H_{Df} = \frac{2\ d_{Df}}{5280\ V_{Df}} + H_{1Df} + H_{2Df}$$

N_{Df} = Number of forklift trucks available for movement D

$$n_{Df} = \frac{N_{Df}\ S}{H_{Df}}$$

M_f = Number of measurement tons per forklift truck

$$D_f = n_{Df}\ M_f\ W\ G\ L$$

(5) Total cargo movement D

D = Total rate of movement to staging area by rail, truck, straddle carrier, and forklift truck in measurement tons per month

$$D = 30\ (D_R + D_v + D_s + D_f)$$

e. Cargo movement E from staging area to wharf

(1) Rail

R_E = Movement rate from staging area to wharf by rail in measurement tons per day

n_{ER} = Number of railcar loads that can be moved from staging area to wharf per day

$$H_{ER} = \frac{2\ d_{ER}}{5280\ V_{ER}} + H_{1ER} + H_{2ER}$$

$$n_{ER} = \frac{N_{1E}\ N_{2E}\ S}{H_{ER}}$$

M_R = Number of measurement tons per railcar

R_E = $n_{ER} \, M_R \, W \, G \, L$

(2) Truck

E_v = Movement rate from staging area to wharf by truck in measurement tons per day

n_{Ev} = Number of truckloads that can be moved from staging area to wharf per day

$$H_{Ev} = \frac{2 \, d_{Ev}}{5280 \, V_{Ev}} + H_{1Ev} + H_{2Ev}$$

N_{Ev} = Number of trucks available for movement E

$$n_{Ev} = \frac{N_{Ev} \, S}{H_{Ev}}$$

M_v = Number of measurement tons per truck

E_v = $n_E \, M_v \, W \, G \, L$

(3) Straddle carrier

E_s = Movement rate from staging area to wharf by straddle carrier in measurement tons per day

n_{ES} = Number of straddle-carrier loads that can be moved from staging area to wharf per day

$$H_{Es} = \frac{2 \, d_{Es}}{5280 \, V_{Es}} + H_{1Es} + H_{2Es}$$

N_{Es} = Number of straddle carriers available for movement E

$$n_{Es} = \frac{N_{Es} \, S}{H_{Es}}$$

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M_s = Number of measurement tons per straddle carrier

$$E_s = n_{Es} \, M_s \ W \ G \ L$$

(4) Forklift truck

E_f = Movement rate from staging area to wharf by forklift truck in measurement tons per day

n_{Ef} = Number of forklift truckloads that can be moved from staging area to wharf per day

$$H_{Ef} = \frac{2 \ d_{Ef}}{5280 \ V_{Ef}} + H_{1Ef} + H_{2Ef}$$

N_{Ef} = Number of forklift trucks available for movement E

$$n_{Ef} = \frac{N_{Ef} \ S}{H_{Ef}}$$

M_f = Number of measurement tons per forklift truck

$$E_f = n_{Ef} \, M_f \ W \ G \ L$$

(5) Total cargo movement E

E = Total rate of movement to wharf by rail, truck, straddle carrier, and forklift truck in measurement tons per month

$$E = 30 \, (E_R + E_v + E_s + E_f)$$

f. Cargo movement F from wharf/anchorage to ship (for detailed equations for movement F, see sec V, para D)

(1) Break-bulk berth (ship's gear)

(2) Container berth (container crane)

(3) LASH/SEABEE berth/anchorage (ship's gantry/ elevator)

(4) RORO berth (vehicle)

3. Removal of Empties Used to Transport Cargo to Ship

The calculation for the removal of empties cannot be pinpointed in the sequence of events on Figure 1, since the removal of empties might occur at almost any stage from the classification and disposition yard to the wharf itself. However, wherever the unloading does occur, the movement rate is already known from previous calculations. Then, to determine if a constraint exists, this rate is traced back through the path that the empties would follow.

a. Rail - calculate number of empties removed by rail per month; that is, containers, railcars, piggy back, and so forth.

b. Truck - calculate number of empties removed by truck per month; that is, containers, trailers, and so forth. Calculate the sum of the rail and truck empties and compare this sum with the monthly rate of influx for the weak link to determine if the removal rate of empties can sustain operations.

C. IN-TRANSIT HOLDING

After examining the various stages in the cargo movement process, the size of the holding area must be examined to determine if it restricts throughput capacity. The holding areas in a terminal are designed to accumulate ocean cargo prior to the ship's arrival. This allows the port operator time to devise a realistic ship stowage plan before the vessel arrives. The various possible combinations of cargo type and destination preclude indiscriminate loading of cargo aboard ships. The amount of cargo, Q, to be stored in the holding area will depend upon the amount of cargo to be loaded on each ship, the time it takes to process and load the cargo, and the scheduling of ship arrivals. Knowing these items, we can calculate two important values: $\overline{Q}$, the average cargo in holding; and $\widehat{Q}$, the maximum cargo in holding. Graphically, the amount of cargo in holding compared with the time for each ship is assumed to be as shown in Figure 2.

The graph shows straight lines resulting from the necessary assumption of uniform rates to simplify the mathematics. Cargo begins arriving in port on a schedule of not earlier than (NET) X days before the ship arrives. Cargo will arrive and accumulate in the holding area at a uniform rate until the cutoff time of not later than (NLT) Y days before ship arrival. This period is t_a. The holding time, t_h,

A - First cargo arrives   E - Loading begins

B - Last cargo arrives   F - Loading ends

C - Ship capacity   G - Ship clears port

D - Ship arrives   H - Next ship arrives
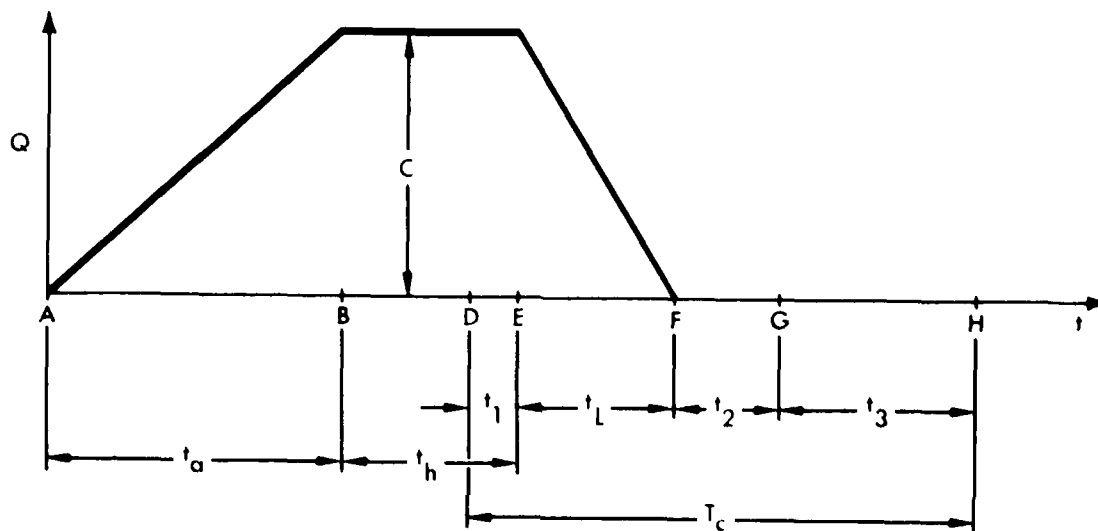
Figure 2.   The Amount of Cargo in the Holding Area.

is the period that all cargo is held in in-transit storage. That is, the time between last cargo arrival and ship loading. Finally, loading is done at a uniform rate during the period t_L.

The period t_1 represents berthing time, when the ship has arrived in port but is not ready for loading. The period t_2 is the period when the ship prepares to sail. Time t_3 is the period before the next ship arrives. The sum of t_1, t_2, t_3, and t_L is the cycle time between ships, T_c.

The schedule for cargo to arrive at the port is based on the ship arrival schedule. However, normally there is some cargo processing to be done between the time cargo arrives and the time it enters the holding area. Also some of the cargo is taken out of the holding area before loading begins for pre-positioning on the wharf, but these small effects are neglected to simplify the mathematics. The value C is the amount of cargo to be loaded on each ship. Knowing the NET X and NLT Y times, the amount of cargo C, and the time it takes to load the cargo, t_L, we can find $\overline{Q}$ and $\widehat{Q}$. First, determine in hours

$$t_a = 24 \, (X - Y + 1)$$

$$t_h = 24 \, (Y - 1) + t_1$$

$$\text{and } T_c = t_1 + t_2 + t_3 + t_L$$

The average amount of cargo in holding is found by determining the area under the curve in the diagram (the quantity-time integral), and then dividing it by the ship cycle time. Thus, per berth,

$$\overline{Q} = C \left[\frac{t_h + 1/2 \, (t_a + t_L)}{T_c} \right]$$

assuming that all ships at the berth are of size C, or that they average that size. Note that $\overline{Q}$ can be greater or less than C depending upon the t values.

To determine $\widehat{Q}$, check the conditions in each of the following cases, and use the appropriate formula.

Case I (fig 3)

If $T_c \geq t_a + t_h$, and $t_a \geq t_L$, then $\widehat{Q} = C$
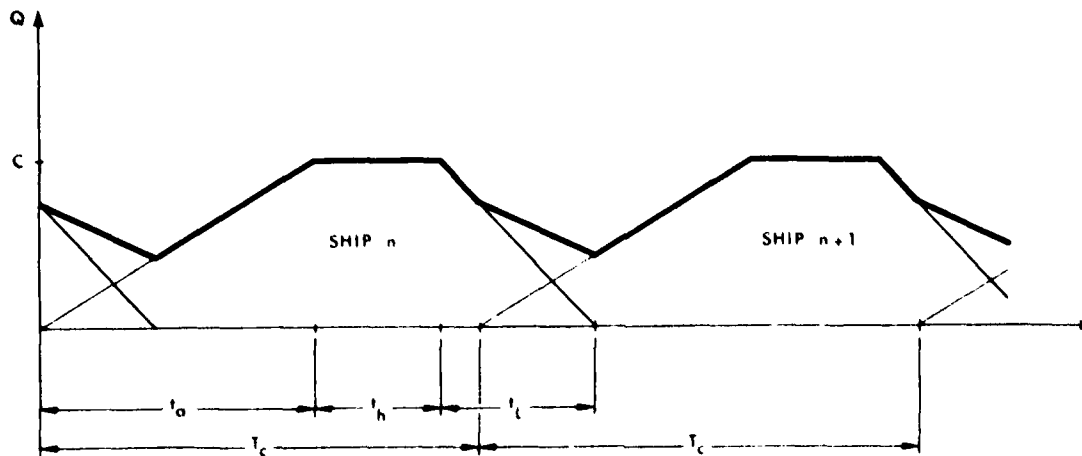
Figure 3. Holding Requirement for Case I.

In this case, cargo is loaded faster than it accumulates; so, if the operations coincide, the holding area inventory will decline. So long as no cargo begins to arrive for the next ship before the loading of the current ship commences, the inventory will not exceed C.

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Case II (fig 4)

If $T_c \geq t_h + t_L$, and $t_a < t_L$, then $\hat{Q} = C$

In this situation, cargo arrives faster than it is loaded; so, if the operations coincide, the holding area inventory will rise. So long as loading of the current ship ceases before all the cargo for the next ship has arrived, the inventory will not exceed C.
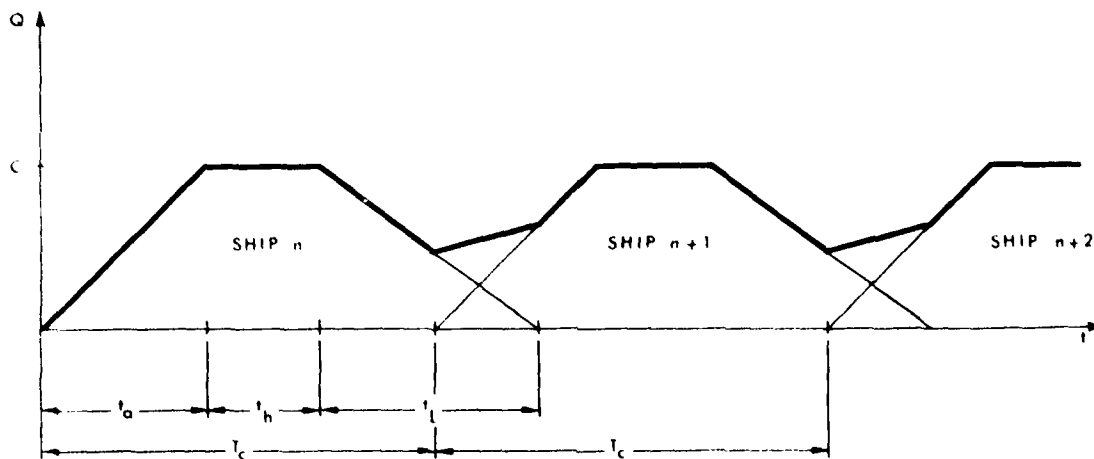
Figure 4. Holding Requirement for Case II.

Case III (fig 5)

If $\dfrac{t_a + t_h}{2} \leq T_c < t_a + t_h$, and $t_a \geq t_L$,

then, $\hat{Q} = C + \dfrac{C}{t_a}(t_a + t_h - T_c)$

$= 2C - \dfrac{C}{t_a}(T_c - t_h)$

Because loading is as fast as or faster than cargo arrival, inventory will remain constant or decline when operations coincide. Cargo for the next ship will arrive before loading of the current ship commences, but cargo for the second following ship will not be arriving. The inventory will rise above C by the amount of cargo for the next ship that arrives, before loading of the current ship begins, since, at that point, the inventory will level off or decline.
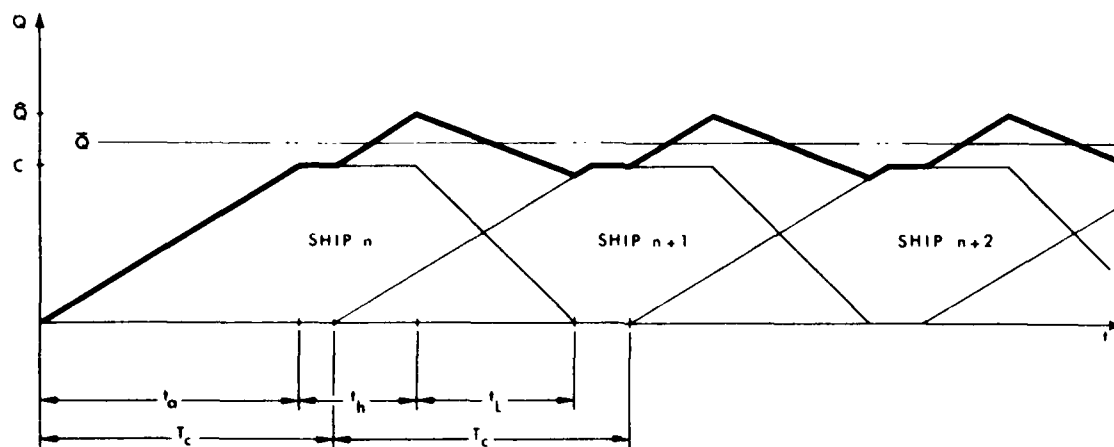
Figure 5. Holding Requirement for Case III.

Case IV (fig 6) NOTE: This case should not be common, since, for Q to increase, either t_h has to increase, or the nonloading time in T_c (that is, t_1, t_2, and t_3) must decrease. The first is inefficient, and the second is probably impossible.

If $T_c < t_h + t_L$, and $t_a < t_L$

then, $\widehat{Q} = C + \dfrac{C}{t_L} (t_h + t_L - T_c)$

$$= 2C - \dfrac{C}{t_L} (T_c - t_h)$$

Since cargo loading is slower than the arrival rate, inventory rises if these operations coincide. Cargo for the next ship has arrived before loading of the current ship ceases. Inventory will rise above C by the amount of cargo still to be loaded on the current ship when all the cargo for the next ship has arrived; at that point, inventory begins to decline.

Case V (fig 7)

If $2T_c < t_a + t_h$, and $t_a > t_L$, $\widehat{Q}$ can be approximated by $\widehat{Q} = 1.10 \, \overline{Q}$

Many examples were studied for Case V and the results showed this to be a good approximation for $\widehat{Q}$. The peak inventory, $\widehat{Q}$, is about 10 percent greater than the average inventory, $\overline{Q}$.

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Figure 6.   Holding Requirement for Case IV.

Figure 7.   Holding Requirement for Case V.

In this situation, ships can be loaded and cleared from the port so rapidly that two or more ships can be cleared in the time it takes to prepare the cargo of one ship for loading.   Furthermore, in most

realistic types of port operation, this situation is probably unachievable except in very high throughput situations where the holding area is not a restriction.

In some cases, a high degree of accuracy may be desired and an accurate log can be maintained to determine the exact amount of cargo in 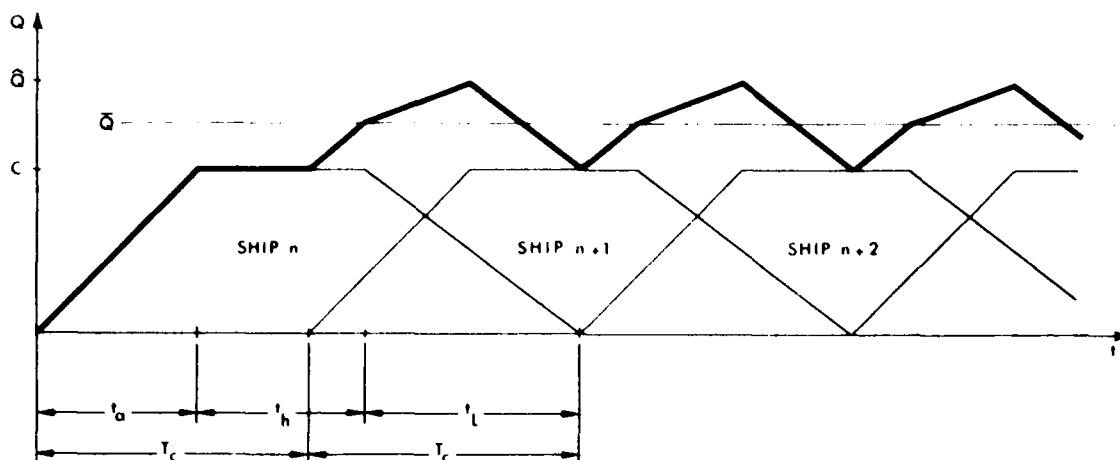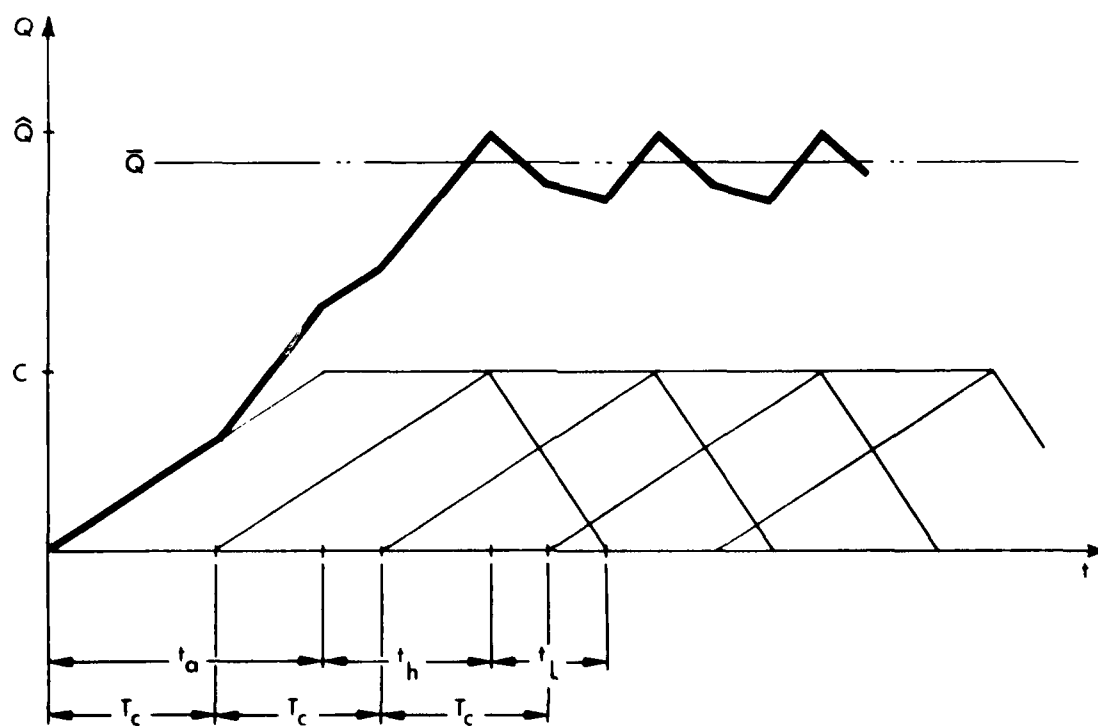the holding area. The following example illustrates a method which can be used for this case. The format of Table III shows a simple accounting system useful for making the tabulation. Assume the following conditions:

$$C \;=\; 1,200 \text{ containers}$$
$$t_a \;=\; 4 \text{ days}$$
$$t_h \;=\; 2 \text{ days}$$
$$t_L \;=\; 3 \text{ days}$$
$$T_c \;=\; 2 \text{ days}$$

As seen from the graph for Case V, if the cargo arrival time, t_a, is 4 days, and the ship capacity, C, is 1,200 containers, then the cargo arrival rate for any ship is 300 containers per day, and, similarly, the cargo-loading rate is 400 containers per day. Q_{in} is defined as the number of containers in a given day for a given ship that come into the holding area. Q_{out} is defined as the number of containers that are taken out of the holding area in a given day for a given ship. $\sum Q_T$ is defined as the cumulative total number of containers that are in the holding area. From Table III, it is seen that Ship n is dropped from the table after Day 10 for this particular example because nothing else happens to Ship n. By Day 10 the cargo for Ship n has already been received and shipped. A few days later Ship n+1 would be dropped from the table, and so forth. Of course, each time a ship is dropped from the table, another one in the sequence is added. Note that on Day 8 the maximum number of containers in the holding area is 3,400.

Using the equation for Case V, $\widehat{Q}$, the maximum number of containers was calculated to be 3,300 containers, which is very close to the value of 3,400 containers obtained from Table III. Therefore, it is more practical to use the approximate equation for $\widehat{Q}$ instead of the exact method presented in Table III. Many different examples were calculated and the approximate equation never yielded results that differed from the exact value by more than 5 percent. Therefore, the expected error in $\widehat{Q}$ for Case V, using the approximate equation, is about $\pm\ 5\%$.

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TABLE III
EXAMPLE FOR CASE V

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		Q_{in}	Q_{out}	$Q_{in}-Q_{out}$	$\Sigma\,Q_T$
Day 1	Ship n	300		300	300
	Ship n+1				300
	Ship n+2				300
	Ship n+3				300
					300
					300
Day 2	Ship n	300		300	600
	Ship n+1				600
	Ship n+2				600
	Ship n+3				600
					600
					600
Day 3	Ship n	300		300	900
	Ship n+1	300		300	1,200
	Ship n+2				1,200
	Ship n+3				1,200
					1,200
					1,200
Day 4	Ship n	300		300	1,500
	Ship n+1	300		300	1,800
	Ship n+2				1,800
	Ship n+3				1,800
					1,800
					1,800
Day 5	Ship n				1,800
	Ship n+1	300		300	2,100
	Ship n+2	300		300	2,400
	Ship n+3				2,400
					2,400
Day 6	Ship n				
	Ship n+1	300		300	2,700
	Ship n+2	300		300	3,000
	Ship n+3				3,000
					3,000
					3,000
Day 7	Ship n		400	−400	2,600
	Ship n+1				2,600
	Ship n+2	300		300	2,900
	Ship n+3	300		300	3,200
					3,200
					3,200
Day 8	Ship n		400	−400	2,800
	Ship n+1				2,800
	Ship n+2	300		300	3,100
	Ship n+3	300		300	3,400
					3,400
					3,400
Day 9	Ship n		400	−400	3,000
	Ship n+1		400	400	2,600
	Ship n+2				2,600
	Ship n+3	300		300	2,900
	Ship n+4	300		300	3,200
					3,200
Day 10	Ship n				3,200
	Ship n+1		400	−400	2,800
	Ship n+2				2,800
	Ship n+3	300		300	3,100
	Ship n+4	300		300	3,400
	Ship n+5				3,400
Day 11	Ship n+1		400	−400	3,000
	Ship n+2		400	−400	2,600
	Ship n+3				2,600
	Ship n+4	300		300	2,900
	Ship n+5	300		300	3,200
	Ship n+6				3,200

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D. BERTH THROUGHPUT: EQUATIONS AND EXAMPLES

One of the most important steps in the flow of cargo through the terminal is at the berth. The derivation of the following equations followed the pattern found in an old report. [12/] However, many more factors are included in the derivation, such as, effects of dredging, night operations, shift changes, and so forth. The berth throughput equations are expressed in units of MTON per month, but the container, LASH/SEABEE, and RORO berth throughput equations are also expressed in units of number of containers per month, number of barges per month, and number of vehicles per month, respectively. The following derivations are illustrated with numerical examples using the nomenclature of Figure 1:

Cargo movement F between the wharf and the ship.

F_t = Total berth throughput rate to and from the ship in measurement tons per month for break-bulk, container, LASH/SEABEE, and RORO

$$F_t = F_g + F_c + F_b + F_r$$

F_g = Berth throughput rate to and from the ship in measurement tons per month for general cargo (break-bulk)

F_c = Berth throughput rate to and from the ship in measurement tons per month for container

F_b = Berth throughput rate to and from the ship in measurement tons per month for LASH/SEABEE

F_r = Berth throughput rate to and from the ship in number of vehicles per month for RORO

s = $1-s_1$, the dredging factor, where s_1 is the fraction of total time lost due to dredging, the value is supplied by the user as it pertains to operations at the particular type of berth as determined by local conditions. The dredging factor is to be used only if a yearly estimate of berth throughput is needed.

The dredging factor cannot be realistically applied to a monthly figure because dredging is not done every month, and applying the factor

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[12/] Port Capacity Methodologies, US Army Transportation Intelligence Agency, Washington, DC, 1955

would change the number of ships per month and the ship cycle time. Actually, the berth would operate month after month unaffected by dredging, then cease operations completely while dredging was in progress. Therefore, the annual berth output is 12 times s times the monthly berth output. W, the weather factor, G, the night productivity factor, and L, the shift-change factor, were previously defined, and the values are supplied by the user as they pertain to operations at the particular type of berth.

1. General Cargo (Break-Bulk) Berth

F_g = Berth throughput rate for general cargo (break-bulk) MTON per month

t_L = Total time required to load or unload ship, in hours

S_i = Stevedore loading or unloading rate, MTON/hour/gang by commodity at hatch number i, where i is a variable number with values between 1 and n

H_i = Capacity of ship's hatch number i, MTON

$(1+f)$ = Effective number of gangs per hatch

f = Efficiency of second gang when two gangs work one hatch $f < 1$,
$f = 0$ for one gang per hatch

P_i = Loading or unloading and securing rate for deck cargo in MTON per hour for one gang, at hatch i

D_i = Total deckload in MTON, at hatch i

N = Number of ships per month

T_c = Ship cycle time in hours

t_1 = Average time to berth, process papers, and start loading or unloading, hours per ship

t_2 = Average time to prepare ship for sailing after loading or unloading, hours per ship

t_3 = Dead time, average time after a ship has sailed and before another ship starts to berth, hours per ship

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NOTE: Values for W, G, L, and s must be supplied as they pertain to break-bulk operations.

PROCEDURE

Equations used to determine:

Minimum time required to load typical break-bulk ship

$$t_L = \frac{1}{WGL} \left[\begin{array}{c} \max \\ i = 1,\ldots, n \end{array} t_i \right] \tag{1}$$

$$\text{where} \quad t_i = \frac{1}{1+f} \left[\frac{H_i}{S_i} + \frac{D_i}{P_i} \right]$$

Whichever hatch requires the maximum loading time represents the minimum time in which the vessel can be loaded (or unloaded), and is, therefore, the controlling hatch.

In case all the hatches were being loaded sequentially, not simultaneously, the minimum time required to load the ship would be calculated by summing all the terms in equation (1) rather than using the time required to load the controlling hatch only.

Ship cycle time T_c

$$T_c = t_L + t_1 + t_2 + t_3 \tag{2}$$

Number of ships per month

$$N = \frac{720}{T_c} \tag{3}$$

Berth throughput rate in MTON per month

$$F_g = NC \tag{4}$$

NOTE: If several different types of ships are to be used, determine MTON per month for each, then, use t_L and the number of each type to find portion of MTON per month for each type; then, total MTON per month per berth.

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EXAMPLE

Find: F_g for a berth capable of accommodating vessel type
VCZ-S-APZ

Known:

C   = Ship capacity, 5,665 MTON

t_1 = Average time to berth, process papers, and start loading
       or unloading, 11 hours per ship

t_2 = Average time to prepare ship for sailing after loading or
       unloading, 9 hours per ship

t_3 = Dead time, 0 hours per ship for maximum berth throughput

W   = Weather factor with an average time loss of 70 hours per
       month due to weather, W = 0.9028

G   = Night-productivity factor, which accounts for time loss due
       to reduced visibility; for two 12-hour shifts per day,
       G = 0.8750

L   = Shift-change factor, with an average time loss of 60 hours
       per month due to shift changes, L = 0.9167

s   = Dredging factor, with an average time loss of 72 hours per
       year due to dredging of berth, s = 0.9917

VESSEL CHARACTERISTICS

Hatch Number i	Hatch Capacity MTON H	Rig and Gangs	Commodity Stevedore Rate MTON/HR/GANG S
1	880	Single, f=0	15
2	960	Single, f=0	15
3	1,702	Double, f=0.8	18
4	1,254	Double, f=0.8	18
5	869	Single, f=0	20
	5,665 Total		

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Where $(1+f)$ = Number of gangs, f is 0 for 1, and f is .8 for 2
There is no deck cargo, therefore D_L is 0

Equations used to determine: (Equations 1 through 4 are developed in procedure section.)

$$t_L = \underset{i=1,\ldots,n}{MAX} \left[\frac{H_i}{S_i} + \frac{D_i}{P_i} \right] \frac{1}{WGL(1+f)}$$

$$t_L = \frac{MAX}{WGL} \left[\frac{880}{15}, \frac{960}{15}, \frac{1702}{(1+.8)18}, \frac{1254}{(1+.8)18}, \frac{869}{20} \right] + 0$$

$$\frac{MAX}{WGL} \left[(58.77), (64.00), (52.53), (38.70), (43.45) \right]$$

Hatch number 2 controls, therefore

$$t_L = \frac{64.0}{WGL} = \frac{64.0}{(0.9028)(0.8750)(0.9167)} = 88.38 \text{ hours} \tag{1}$$

T_c from equation (2)

$$T_c = t_L + t_1 + t_2 + t_3$$

$t_3 = 0$, for maximum berth output

therefore, $T_c = T_{c,min}$, $N = N_{max}$, and $F_g = F_{g,max}$

$$T_{c,min} = 88.38 + 11.00 + 9.000$$

$$= 108.4 \text{ hours} \tag{2}$$

Number of ships required per month, using equation (3)

$$N_{max} = \frac{720}{T_{c,min}}$$

$$= \frac{720}{108.4} = 6.642 \text{ ships per month} \tag{3}$$

Using this value with equation (4)

MTON per month

$$F_{g, \, max} = N_{max} \, C$$

$$= (6.642 \text{ ships per month}) \, (5,665 \text{ MTON per ship})$$

$$= 37,630 \text{ MTON per month} \tag{4}$$

Output from this berth, using vessel type VCZ-S-APZ, with other conditions as indicated, is 37,630 MTON per month.
Effect of dredging on the annual berth output
Multiply 12 s times the monthly berth output.

$$(12) \, (0.9917) \, (37,630)$$
$$447,800 \text{ MTON per year}$$

2. Container Berth

F_c = Berth throughput rate for containerships, MTON per month

F_c' = Berth throughput rate for containerships, number of containers per month

P = Average payload per container in MTON

C = Capacity of containerships to be loaded or unloaded, average number of containers per ship

N = Number of ships per month

n = Number of container cranes

A = Container crane rate for one crane, number of containers per hour

t_1 = Average time to berth, process papers, and start loading or unloading, hours per ship

t_2 = Average time to prepare ship for sailing after loading or unloading, hours per ship

t_3 = Dead time, average time after a ship has sailed and before another ship starts to berth, hours per ship

NOTE: Values for W, G, L, and s must be supplied as they pertain to container berth operations.

PROCEDURE

Equations used to determine:

Minimum time needed to load typical containership

$$t_L = \frac{C}{N\ A\ WGL} \tag{5}$$

Ship cycle time T_c

$$T_c = t_L + t_1 + t_2 + t_3 \tag{6}$$

Number of ships per month

$$N = \frac{720}{T_c} \tag{7}$$

Number of containers per month

$$F_c' = NC \tag{8}$$

Number of MTON per month

$$F_c = P\ F_c' \tag{9}$$

EXAMPLE

Find F_c for the following conditions

Known:

P = Payload per container, 10 MTON

C = Ship capacity, 800 containers per ship

n = Number of container cranes at berth, 2

A = Container crane rate, 15 containers per hour

t_1 = Average time to berth, process papers, and start loading, 11 hours per ship

t_2 = Average time to prepare ship for sailing after loading, 9 hours per ship

t_3 = Dead time, 0 hours per ship for maximum berth through-put

W = Weather factor with an average time loss of 50 hours per month due to weather, $W = 0.9306$

G = Night productivity factor, which accounts for a time loss due to reduced visibility; for two 12-hour shifts

$$\left[12 - (.75 \times 12) \right] \; 30 = 90 \text{ hours per month, gives}$$
$$G = 0.8750$$

L = Shift-change factor with an average time loss of 60 hours per month due to shift changes, $L = 0.9167$

s = Dredging factor with an average time loss of 50 hours per year due to dredging, $s = 0.9942$

Determine:

t_L from equation (5)

$$t_L = \frac{C}{n \; A \; WGL}$$

$$= \frac{800}{2 \; (15) \; (0.9306) \; (0.8750) \; (0.9167)}$$

$$= 37.72 \text{ hours}$$

T_c from equation (6)

$$T_c = t_L + t_1 + t_2 + t_3$$

$$t_3 = 0 \text{ for maximum berth output}$$

therefore, $T_c = T_{c, \; min}, \quad N = N_{max}$

and $\quad F_c = F_{c, \; max}$

$$T_{c, \; min} = 35.72 + 11.00 + 9.000$$

$$= 55.72 \text{ hours} \tag{6}$$

Number of ships required per month using equation (7)

$$N_{max} = \frac{720}{T_{c, \, min}}$$

$$= \frac{720}{55.72}$$

$$= 12.92 \text{ ships per month} \qquad (7)$$

Number of containers per month, using equation (8)

$$F_c' = NC$$

$$= (12.92)(800)$$

$$= 10,340 \text{ containers per month} \qquad (8)$$

Number of MTON per month, using equation (9)

$$F_c = P \, F_c'$$

$$= (10)(10,340)$$

$$= 103,400 \text{ MTON per month} \qquad (9)$$

Effect of dredging on the annual berth output

Multiply 12 times s times the monthly berth output

$$(12)(0.9942)(103,400)$$
$$1,234,000 \text{ MTON per year}$$

3. **LASH/SEABEE Berth/Anchorage**

F_b = Berth throughput rate for barge ships, MTON per month

F_b' = Berth throughput rate for barge ships, number of barges per month

P_b = Average payload per barge, MTON

C = Capacity of barge ships to be loaded or unloaded, average number of barges per ship

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N = Number of ships per month

A = Barge crane or elevator rate, average number of barges per hour, onloaded or offloaded at berth or anchorage (if ship has to unload, divide A by 2)

t_1 = Average time to berth, process papers, and start loading or unloading, hours per ship

t_2 = Average time to prepare ship for sailing after loading or unloading, hours per ship

t_3 = Dead time, average time after a ship has sailed and before another ship starts to berth, hours per ship

NOTE: Values for W, G, L, and s must be supplied as they pertain to barge-ship-type operations.

Equations used to determine:

Minimum time to load typical barge ship

$$t_L = \frac{C}{A\ WGL} \tag{10}$$

Ship cycle time, T_c

$$T_c = t_L + t_1 + t_2 + t_3 \tag{11}$$

Number of ships per month

$$N = \frac{720}{T_c} \tag{12}$$

Berth throughput rate in number of barges per month

$$F_b' = NC \tag{13}$$

Berth throughput rate in number of MTON per month

$$F_b = P_b\ F_b' \tag{14}$$

EXAMPLE

LASH ships are to arrive empty with no barges on the ship, and are to be loaded.

Find F_b for following conditions

Known:

P_b = Payload per barge, 350 MTON

C = Ship capacity, 73 barges

A = Rate of barge crane, 3 per hour

s = Dredging factor; with an average time loss per year due to dredging of berth, 72 hours, s = 0.9917

W = Weather factor; with an average time loss of 50 hours per month due to weather, W = 0.9306

L = Shift-change factor, with an average time loss of 60 hours per month due to shift changes, L = 0.9167

G = Night-productivity factor, with an average time loss of 90 hours per month due to reduced visibility, G = 0.8750

t_1 = Average time to berth, process papers, and start loading, 11 hours per ship

t_2 = Average time to prepare ship for sailing after loading, 9 hours per ship

t_3 = Dead time, 0 hours per ship for maximum berth throughput

Determine:

t_L from equation (10)

$$t_L = \frac{C}{A\ WGL}$$

$$= \frac{73}{(3)\,(0.9306)\,(0.8750)\,(0.9167)} = 32.60 \text{ hours} \qquad (10)$$

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T_c from equation (11)

$$T_c = t_L + t_1 + t_2 + t_3$$

$$t_3 = 0, \text{ for maximum berth output}$$

therefore, $T_c = T_{c, min}$, $N = N_{max}$, and $F_b = F_{b, max}$

$$T_{c, min} = 32.60 + 11.00 + 9.000$$

$$= 52.60 \text{ hours} \qquad (11)$$

Number of ships required per month, using equation (12)

$$N_{max} = \frac{720}{T_{c, min}}$$

$$= \frac{720}{52.60}$$

$$= 13.69 \text{ ships per month} \qquad (12)$$

Berth throughput rate in number of barges per month, using equation (13)

$$F_b' = NC$$

$$= (13.69)(73)$$

$$= 999.4 \text{ barges per month} \qquad (13)$$

Berth throughput rate in number of MTON per month, using equation (14)

$$F_b = P_b F_b'$$

$$= (350)(999.4)$$

$$= 349,800 \text{ MTON per month} \qquad (14)$$

Effect of dredging on the annual berth output

Multiply 12 times s times the monthly berth output

$$(12)(0.9917)(349,800)$$

$$4,163,000 \text{ MTON per year}$$

4. Roll-On/Roll-Off Berth

F_r = Berth throughput rate in MTON per month

F_r' = Berth throughput rate in number of vehicles per month

C = Capacity of RORO ships to be loaded or unloaded, average number of vehicles per ship

P_r = Volumetric displacement of each vehicle, in MTON

N = Number of ships per month

n = Number of on-and-off ramps to be used in operation.

A = Ramp loading or unloading rate per ramp, number of vehicles per hour

t_1 = Average time to berth, process papers, and start loading or unloading, hours per ship

t_2 = Average time to prepare ship for sailing after loading or unloading, hours per ship

t_3 = Dead time, average time after a ship has sailed and before another ship starts to berth, hours per ship

NOTE: Values for W, G, L, and s must be supplied as they pertain to RORO-type operations.

Determine:

Minimum time to load typical RORO ship

$$t_L = \frac{C}{n \, A \, WGL} \qquad (15)$$

Ship cycle time, T_c, given by the equation

$$T_c = t_L + t_1 + t_2 + t_3 \qquad (16)$$

Number of ships per month, given by the equation

$$N = \frac{720}{T_c} \qquad (17)$$

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Berth throughput rate in number of vehicles per month, given by the equation

$$F'_r = NC \qquad (18)$$

Berth throughput rate in MTON per month, given by the equation

$$F_r = P_r F'_r \qquad (19)$$

EXAMPLE

Find F_r for the following conditions:

Ships arrive empty. Consider loading vehicles only.

Known:

C   Ship capacity, 500 vehicles (averaging 40 feet each)

P_r Volumetric displacement of each vehicle, 64 MTON

n   Number of ramps, 2

A   Ramp-loading rate, 15 vehicles per hour

t_1 Average time to berth, process papers, and start loading, 11 hours per ship

t_2 Average time to prepare ship for sailing after loading, 9 hours

t_3 Dead time, 0 hours per ship for maximum berth throughput

W   Weather factor, with an average time loss of 50 hours per month due to weather, W = 0.9306

G   Night-productivity factor, with an average time loss of 90 hours per month due to reduced visibility, G = 0.8750

L   Shift-change factor, with an average time loss of 60 hours per month due to shift changes, L = 0.9167

s   Dredging factor, with an average time loss of 72 hours per year due to dredging of berth, s = 0.9917

Determine:

t_L from equation (15)

$$t_L = \frac{C}{nAWGL}$$

$$= \frac{500}{(2)\,(15)\,(0.9306)\,(0.8750)\,(0.9167)}$$

$$= 22.33 \text{ hours} \tag{15}$$

$\underline{T_c \text{ from equation (16)}}$

$$T_c = t_L + t_1 + t_2 + t_3$$

$t_3 = 0$, for maximum berth output; therefore

$$T_c = T_{c,\ min}, \quad N = N_{max}, \quad \text{and } F_r = F_{r,\ max}$$

$$T_{c,\ min} = 22.33 + 11.00 + 9.000$$

$$= 42.33 \text{ hours} \tag{16}$$

Number of ships required per month, using equation (17)

$$N_{max} = \frac{720}{T_{c,\ min}}$$

$$= \frac{720}{42.33}$$

$$= 17.01 \text{ ships per month} \tag{17}$$

Berth throughput rate in number of vehicles per month, given by equation (18)

$$F_r' = NC$$

$$= (17.01)\,(500)$$

$$= 8,505 \text{ vehicles per month} \tag{18}$$

Berth throughput rate in MTON per month, using equation (19)

$$F_r = P_r\,F_r'$$

$$= (64)\,(8,505)$$

$$= 544,300 \text{ MTON per month} \tag{19}$$

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Effect of dredging on the annual berth output

Multiply 12 times s times the monthly berth output

(12) (0.9917) (544, 300)
6, 477, 000 MTON per year

E. EXAMPLE FOR DETERMINING PORT THROUGHPUT

The previous equations have shown how to calculate many factors concerning a port. An example now will be presented for a complete one-berth container port, giving calculations for the movement rate of cargo from input to the port to loading of the ship. The cargo throughput rates will be analyzed for each subsystem, along with the size of the holding yard. The weak link will be identified.

Problem: Calculate the cargo throughput of a one-berth containership port in measurement tons per month and identify the weak link.

Given: Assume the same data and conditions applicable in the previous container berth example, and that the holding yard size is sufficient for 2,000 MILVANs (a standardized 20-foot military container).

Solution: Following the format of Figure 1, cargo movement A will be calculated first.

1. Movement A From Outside the Gate to Inside the Gate

    a. Rail

       N_2 = 50 railcars per train (assume)

       N_3 = 3 trains per day (the maximum number that can be handled at the gate, as determined by the user)

       n_{AR} = $N_2 N_3$

            = 150 railcars per day

       M_R = 30 MTON per railcar (assume 3 MILVANs per railcar)

W = 0.9850 (from local weather data pertaining to this movement)

G = 1.0 (assume no performance loss on night shift for this movement)

L = 1.0 (assume no time loss due to shift change for this movement)

A_R = $n_{AR} M_R W G L$

A_R = 4,433 MTON per day

b. **Truck**

S = 24 hours (two 12-hour shifts)

t_A = 0.0200 hours per truck, or one truck every 72 seconds (this is the maximum that can be handled at the gate, as determined by the user)

n_{Av} = $\dfrac{S}{t_A}$

n_{Av} = 1,200 trucks per day

M_v = 10 MTON per truck (MILVAN)

W = 0.9850 (from weather data pertaining to this movement)

G = 1.0 (assume no performance loss on night shift for this movement)

L = 1.0 (assume no time loss due to shift change for this movement)

A_v = $n_{Av} M_v W G L$

A_v = 11,820 MTON per day

c. **Total**

A = 30 $(A_R + A_v)$ = 487,600 MTON per month

2.   Movement B to Classification and Disposition Yard

   a.   <u>Rail</u>

$$d_{BR} = 2,640 \text{ feet}$$

$$V_{BR} = 1 \text{ mile per hour}$$

H_{1BR}
and
$H_{2BR} = 0$ (assume negligible)

$$H_{BR} = \frac{2d_{BR}}{5,280\ V_{BR}} + H_{1BR} + H_{2BR}$$

$$H_{BR} = 1.0 \text{ hours}$$

$N_{1B} = 1$ locomotive, $N_{2B} = 30$ railcars per train (numbers
are determined by the user)

$$S = 24 \text{ hours}$$

$$n_{BR} = \frac{N_{1B}\ N_{2B}\ S}{H_{BR}}$$

$$n_{BR} = 720 \text{ railcar loads per day}$$

$$B_R = n_{BR}\ M_R\ W\ G\ L$$

$W = 0.9850$, $G = 0.9870$, $L = 1.0$ (pertaining to this
operation)

$$M_R = 30 \text{ MTON per railcar}$$

$$B_R = 21,000 \text{ MTON per day}$$

   b.   <u>Truck</u>

$$d_{Bv} = 2,640 \text{ feet}$$

$$V_{Bv} = 5 \text{ miles per hour}$$

H_{1Bv}
and
$H_{2Bv} = 0$ (assume negligible)

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$$H_{Bv} = \frac{2\ d_{Bv}}{5,280\ V_{Bv}} + H_{1Bv} + H_{2Bv}$$

H_{Bv} = 0.2000 hours

S = 24 shift hours per day

N_{Bv} = 10 trucks

$$n_{Bv} = \frac{N_{Bv}S}{H_{Bv}}$$

n_{Bv} = 1,200 truckloads per day

W = 0.9850, G - 0.8750, L = 1.0 (pertaining to this operation

M_v = 10 MTON per truck

B_v = $n_{Bv}\ M_v$ W G L

B_v = 1,034 MTON per day

c. <u>Total</u>

B = 30 (B_R + B_v) = 661,000 MTON per month

3. <u>Movement C to Holding Yard</u>

a. <u>Rail</u>

d_{CR} = 4,000 feet

V_{CR} = 1.100 miles per hour

H_{1CR}
and
H_{2CR} = 0 (assume negligible)

$$H_{CR} = \frac{2\ d_{CR}}{5,280\ V_{CR}} + H_{1CR} + H_{2CR}$$

H_{CR} = 1,377 hours

N_{1C} = 1 locomotive, N_{2C} = 20 railcars per train

S = 24 hours

$$n_{CR} = \frac{N_{1C}\, N_{2C}\, S}{H_{CR}}$$

n_{CR} = 348.6 railcar loads per day

C_R = $n_{CR}\, M_R\ W\ G\ L$

W = 0.9850, G = 0.8750, L = 1.0 (pertaining to this operation)

M_R = 30 MTON per railcar

C_R = 9,013 MTON per day

b. Truck

d_{CV} = 4,000 feet

V_{Cv} = 6 miles per hour

H_{1Cv}
and
H_{2Cv} = 0 (assume negligible)

$$H_{Cv} = \frac{2\, d_{Cv}}{5,280\, V_{Cv}} + H_{1Cv} + H_{2Cv}$$

H_{Cv} = 0.2525 hour

S = 24 hours

N_{Cv} = 10 trucks

$$n_{Cv} = \frac{N_{Cv}\, S}{H_{Cv}}$$

n_{Cv} = 950 truckloads per day

$$M_v \quad = \quad 10 \text{ MTON per truck}$$

$$C_v \quad = \quad n_{C_v} \, M_v \, W \, G \, L$$

$$W \quad = \quad 0.9850, \; G = 0.8750, \; L = 1.0 \text{ (pertaining to this operation)}$$

$$C_v \quad = \quad 8,188 \text{ MTON per day}$$

   c.   <u>Straddle carrier</u>

$$C_s \quad = \quad 0 \text{ (no straddle carriers)}$$

   d.   <u>Total</u>

$$C \quad = \quad 30 \, (C_R + C_v + C_s) = 516,000 \text{ MTON per month}$$

4. Movement D to Staging Area

Not applicable since MILVANs are already loaded and will be moved directly from holding to the wharf.

5. Movement E to Wharf

   a.   <u>Rail</u>

$$d_{ER} \quad = \quad 5,280 \text{ feet}$$

$$V_{ER} \quad = \quad 2.0 \text{ miles per hour}$$

$$H_{1ER} \text{ and } H_{2ER} = 0$$

$$H_{ER} \quad = \quad \frac{2 \, d_{ER}}{5,280 \, V_{ER}} + H_{1ER} + H_{2ER}$$

$$H_{ER} \quad = \quad 1.0 \text{ hour}$$

$$N_{1E} \quad = \quad 1 \text{ locomotive}, \; N_{2E} = 10 \text{ railcars per train}$$

$$n_{ER} \quad = \quad \frac{N_{1E} \, N_{2E} \, S}{H_{ER}}$$

n_{ER} = 240 railcar loads per day

E_R = $n_{ER}\ M_R\ W\ G\ L$

W = 0.9850, G = 0.8750, L = 1.0 (pertaining to this operation)

M_R = 30 MTON per railcar

E_R = 6,206 MTON per day

b. Truck

d_{Ev} = 5,280 feet

V_{Ev} = 5 miles per hour

H_{1Ev}
and
H_{2Ev} = 0

$$H_{Ev}\ =\ \frac{2\ \ d_{Ev}}{5,280\ V_{Ev}}\ +\ H_{1Ev}\ +\ H_{2Ev}$$

H_{Ev} = 0.40 hours

N_{Ev} = 20 trucks

S = 24 hours

$$n_{Ev}\ =\ \frac{N_{Ev}\ S}{H_{Ev}}$$

n_{Ev} = 1,200 truckloads per day

E_v = $n_{Ev}\ M_v\ W\ G\ L$

M_v = 10 MTON per truck

W = 0.9850, G = 0.8750, L - 1.0 (pertaining to this tion)

E_v = 10,340 MTON per day

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c. Straddle carrier

E_s = 0 (no straddle carriers)

d. Forklift trucks

E_f = 0 (no forklift trucks)

e. Total

E = 30 (E_R + E_v + E_s + E_f) = 496,400 MTON per month

6. Movement F from Wharf to Ship

E = 107,200 MTON per month (see previous example on container berth)

Now, the required size of the holding yard must be calculated and compared with the actual size to determine if a constraint exists. The format for these calculations is found in section V, paragraph c, "In-Transit Holding."

Assume the following for the required cargo arrival time and holding time:

t_a = 2 days

t_h = 2 days

The ship cycle time as calculated from the container-berth example and equation (6) is

T_c = 53.6 hours

therefore,

T_c = 2.23 days

Next, since $t_a > t_L$, examine the following inequality:

Is

$T_c \geq t_a + t_h$?   Case I,

$\dfrac{t_a + t_h}{2} < T_c < t_a + t_h$?   Case III,

$$2T_c < t_a + t_h \quad ? \qquad \text{Case V}$$

$$2 < 2.23 < 4$$

Therefore, as seen from the previous section on in-transit holding, these conditions correspond to case III, and the following equation applies:

$$\hat{Q} = 2C - \frac{C}{t_a}(T_c - t_h) \qquad \text{Case III}$$

$$\hat{Q} = 1.885\,C$$

$$C = 800 \text{ MILVANs}$$

$$\hat{Q} = 1,505 \text{ MILVANs}$$

Therefore, the required maximum holding capacity is 1,505 MILVANs and the available space is 2,000 MILVANs. This means that the holding yard has sufficient space for the example problem, and no constraint is involved with holding. Summarizing, the calculations for movements A through F to identify the weak link:

Movement	Cargo throughput for each link
A	487,600 MTON per month
B	661,000 MTON per month
C	516,000 MTON per month
D	(not applicable)
E	496,400 MTON per month
F	107,200 MTON per month

The weak link is movement F (ship to wharf) at the container berth; the output of the port is therefore limited to 107,200 MTON per month.

F. COMBINED OPERATIONS

The preceding examples have considered only one type of operation. Of course, many ports have combined operations; that is, more than one type of operation going on at different berths at the same time. This complicates the calculations for the holding area because the total space needed in the holding area is not necessarily equal to the sum of the space needed for each and every berth. The total space needed in the holding area may be less than the sum of the peaks of

the individual berths because the peak demand for each berth may not occur at the same instant of time. The following example demonstrates this principle:

EXAMPLE

Determine holding area capacity required to support combined operations at a break-bulk berth, a container berth, and a LASH operation simultaneously, using the following data that are compatible with the preceding berth rate examples.

Break-Bulk:

T_c	=	5 days	t_L	=	3 days
t_a	=	3 days	C	=	6,000 MTON
t_h	=	2 days			

Container:

T_c	=	3 days	t_L	=	1.5 days
t_a	=	2 days	C	=	8,000 MTON
t_h	=	2 days			

LASH:

T_c	=	3 days	t_L	=	1 day
t_a	=	3 days	C	=	25,000 MTON
t_h	=	2 days			

As seen in Figure 8, $\widehat{Q}$ = 6,000 MTON. This result can also be obtained from the equation in Case I of the "In-transit Holding Section." Additionally, $\widehat{Q}$, as shown in Figure 9, or as calculated from the equation in Case III, is 12,000 MTON. Finally, $\widehat{Q}$, as shown in Figure 10, or as calculated from Case III, is 41,670 MTON. Of course, three separate parts of the holding area will sustain operations if each part holds its peak capacity of 6,000 MTON, 12,000 MTON, and 41,670 MTON, respectively. The sum of these values is 59,670 MTON. However, if the peaks of each $\widehat{Q}$ do not occur at the same time, which is most probable, the capacity of the holding area can be smaller than 59,670 MTON and still sustain maximum throughput. The minimum acceptable value shown in Figure 11 is 58,330 MTON. This lower
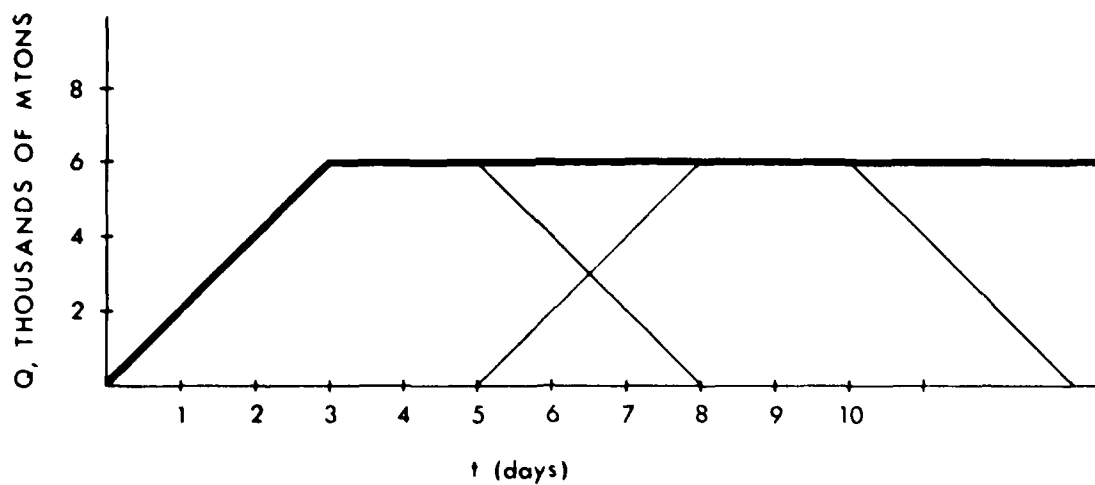
Figure 8. Holding Requirement for Break-Bulk Berth of Combined Operations.
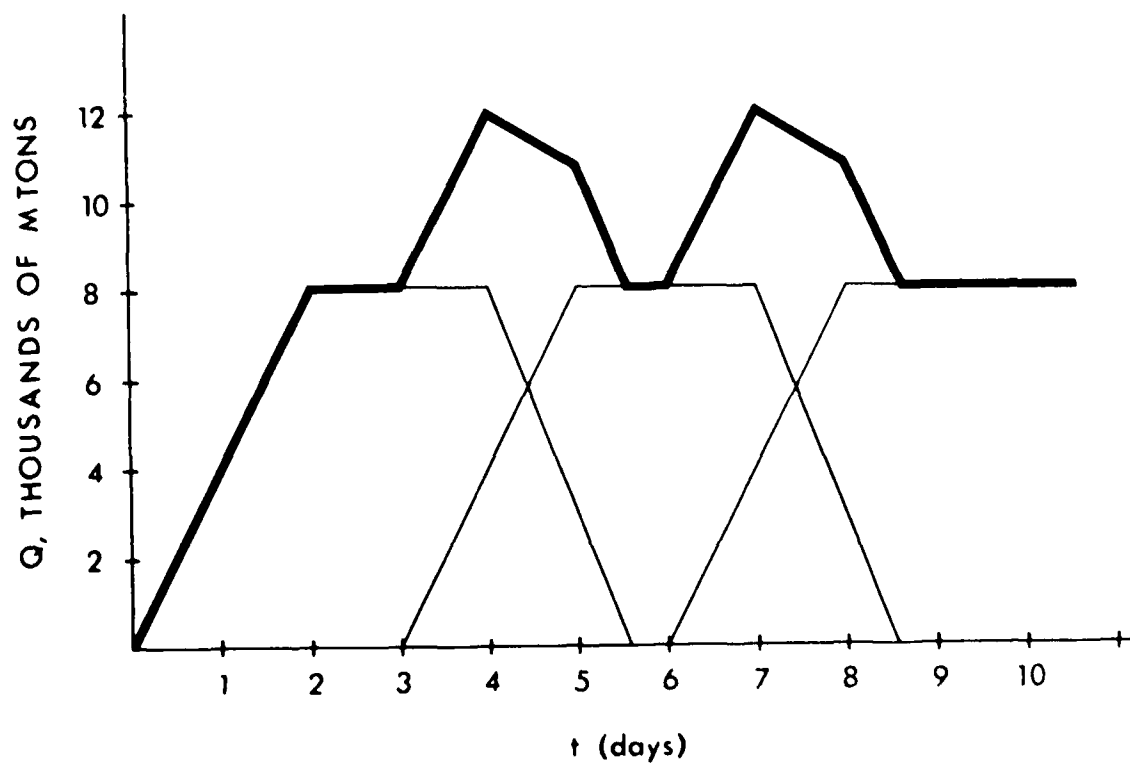
Figure 9. Holding Requirement for Container Berth of Combined Operations.

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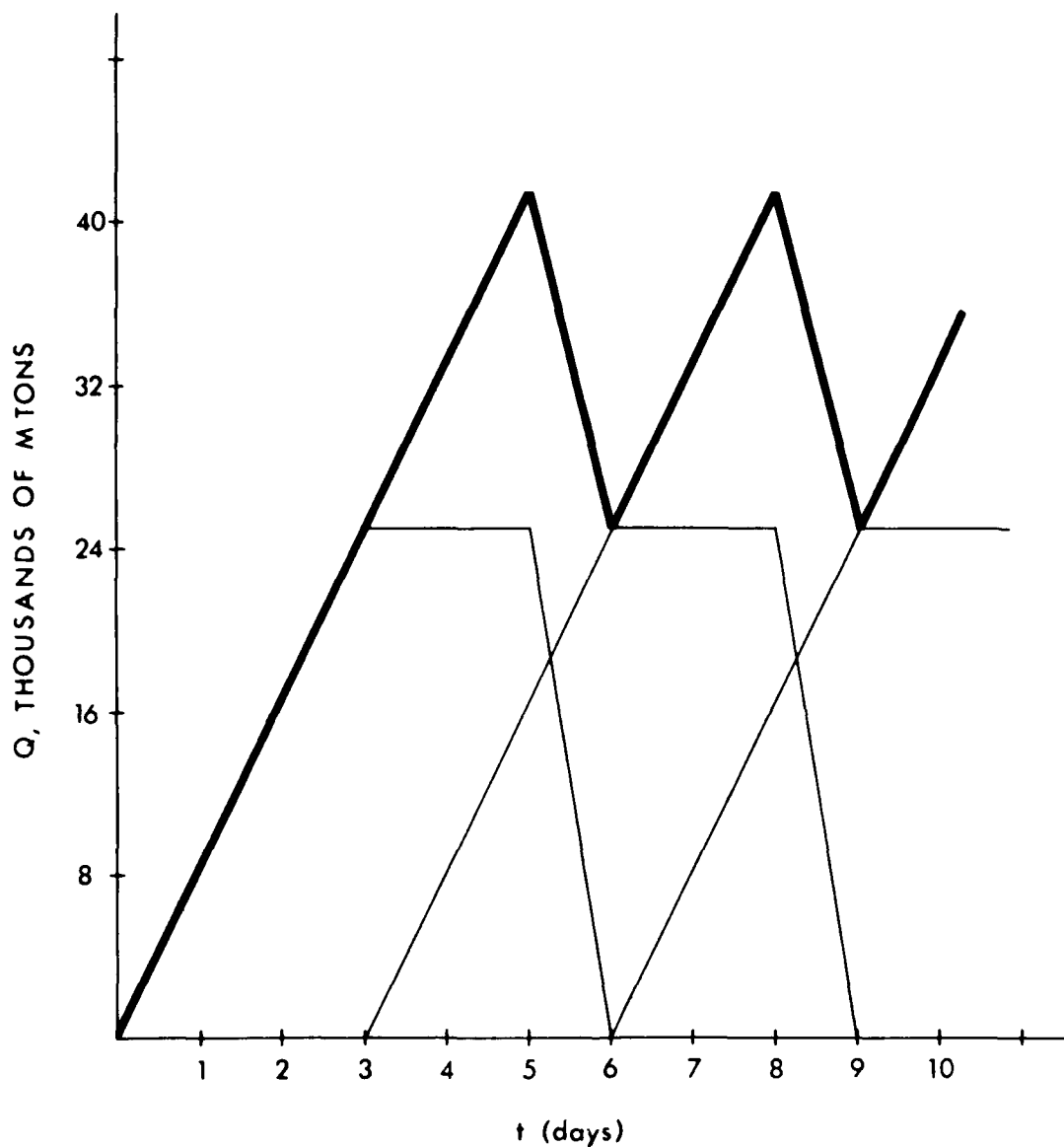
Figure 10.   Holding Requirement for LASH Anchorage of Combined
            Operations.

value results because the peaks of $\widehat{Q}$ occur at different times, namely,
with Break-Bulk, t = 3 days; with Container, t = 4 days; and with LASH,
t = 5 days.   The result is even more dramatic if the ship capacity of
two of the berths is equal, and the principle is demonstrated that the
peaks of $\widehat{Q}$ should occur at different times to maximize holding-area
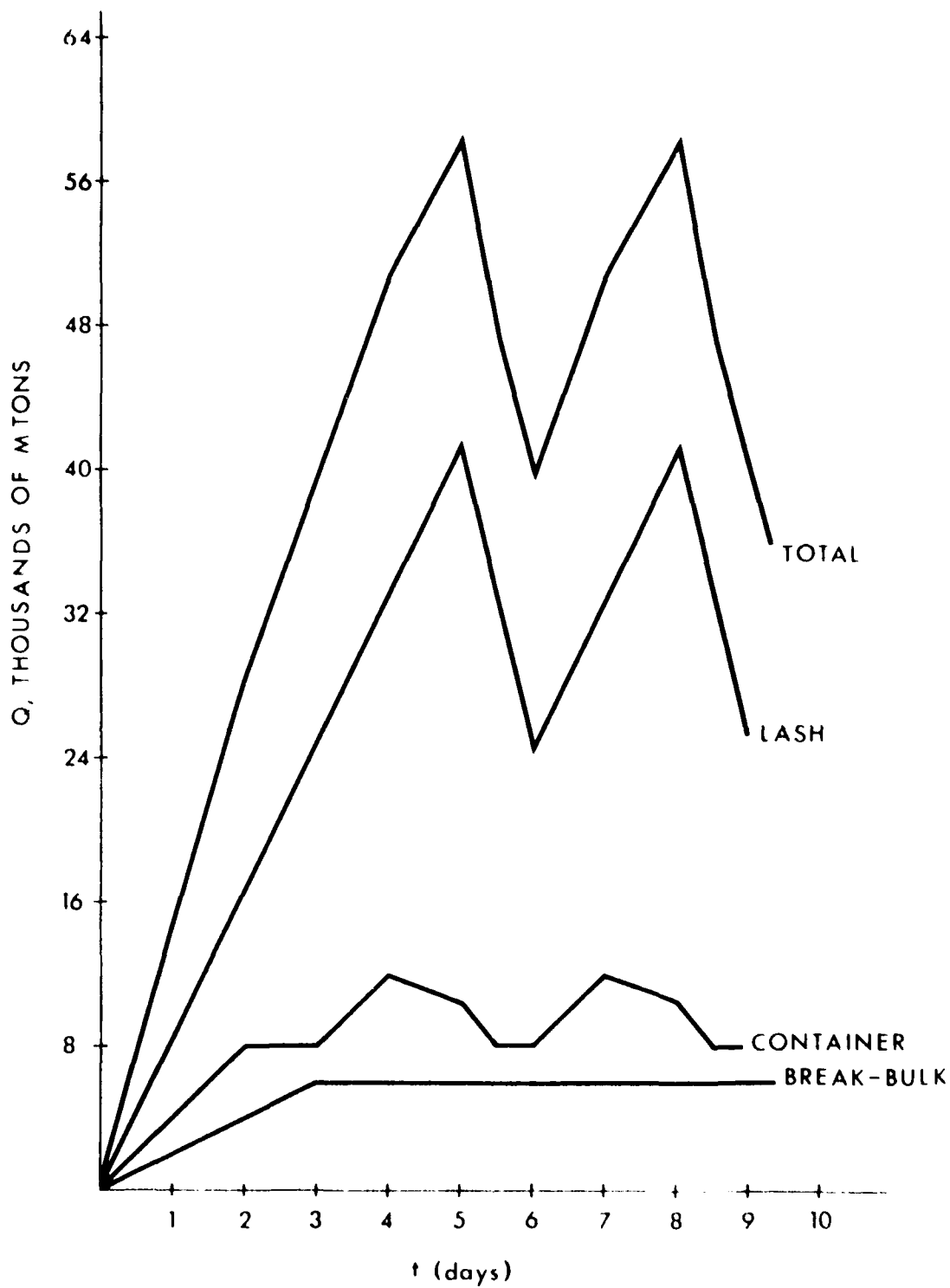
Figure 11. Summation of Holding Requirement for Three Berths of Combined Operations.

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capability. For example, consider two identical berths like the container berth of Figure 9. If $\widehat{Q}$ for both berths occurs at t = 4 days, the holding area for these two berths would have to have a capacity for 24,000 MTON. However, if one berth lagged behind the other one in time by 1.5 days, say t = 4.5 for $\widehat{Q}$, the peak demand would occur at different times and the required holding capacity would be the sum of 12,000 MTON and 8,000 MTON only, or 20,000 MTON instead of 24,000 MTON. This reduction in required holding capacity amounts to 16.7 percent. Combined operations must be given close attention for possible reduction in required holding capacity, since the difference might be the deciding factor as to whether the operation could be carried out with the required cargo throughput.

EXAMPLE

Determine the ship cycle time if the holding area capacity is insufficient. Consider the container berth of Figure 9, and instead of the 12,000-MTON capacity needed in the holding area, only 11,000 MTON is available. The ship capacity cannot be changed, and the cargo arrival and holding times should already be at a minimum for maximum cargo throughput. Therefore, ship cycle time must be lengthened so that the required holding capacity will equal the available holding capacity. The solution can be obtained either graphically (fig 12) or with the use of the equation for $\widehat{Q}$. For this example the governing equation is:

Case III

$$\widehat{Q} = 2C - \frac{C}{t_a} (T_c - t_h)$$

for $\dfrac{t_a + t_h}{2} \le T_c < t_a + t_h$, and $t_a \ge t_L$

Solving for T_c,

$$T_c = \frac{t_a}{C} \left[2C - \widehat{Q} \right] + t_h$$

All the values except Q are the same as those in the previous example.

t_a = 2 days

t_h = 2 days
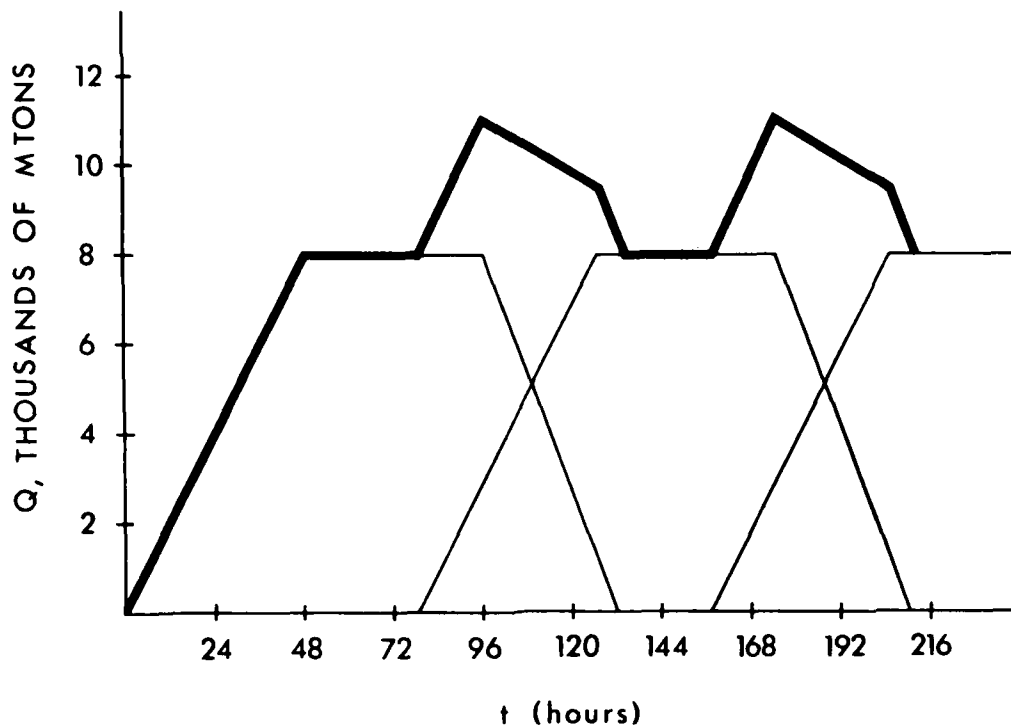
Figure 12. Container Berth With Holding Area Capacity
Limitation of 11, 000 MTON.

$C \quad = \quad 8,000$ MTON

$\widehat{Q}$ is now set equal to 11, 000 MTON, which gives

$T_c \quad = \quad 3.25$ days, or 78 hours

The equations greatly simplify the task of calculating the output of a
port. Much time and expertise would be needed to undertake such a
project without the aid of the equations developed in this methodology.
However, this does not mean that the complex task is now simple;
it means that the task is now less complex. Also, the equations enable
the port operator to experiment with the operations and may result in
a change in the output of the port. Then, the benefit of the resultant
change could be weighed against the cost of producing the change.
Conceivably, a significant benefit could result from a change in which
the cost was easily justified. Also, if a single berth at a port were
not usable due to an operational problem, the adjusted output could
be quickly calculated so the operator would know the capability of the
port.

VI. RECOMMENDATIONS FOR FUTURE WORK

A. Factors should be developed for the throughput equations for container-handling equipment, such as mobile cranes.

B. Procedures should be developed for estimating personnel and equipment requirements to carry out each operation at maximum equipment capability, especially during a period of national emergency.

C. The methodology developed in this study should be validated by actual test in an operating port environment.

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APPENDIX A

SHIPLOADING FACTORS, ACTUAL AND NOTIONAL SHIP FACTORS

EAST AND GULF COASTS

Commodity	Type of Ship		MTON Capacity	Days to Load
General Cargo	C-2		7,500	3 1/2
	C-3		11,500	4
	C-4		12,500	4 1/2
	LASH	(Barges only)	350	1 1/4
	SEABEE		850	1 1/2
Ammunition	C-2		6,000	3
	C-3		10,000	4
	C-4		11,000	5
	LASH	(Barges only)	350	1 1/4
	SEABEE		850	1 1/2
Unit Equipment	C-2		8,000	2 1/2
	C-3		11,000	4
	C-4		13,000	4
	LASH	(Barges only)	350	2 1/4
	SEABEE		850	1 1/2
Container	Containership		24,000	30 Hours
Vehicles	Comet		13,000	13 Hours
	Adm William M. Callaghan		23,000	23 Hours
	LASH	(Barges only)	350	1 1/4
	SEABEE		850	3 1/2
Reefer	C-2		5,500	4

*MTMTS Pam 700-1

EAST AND GULF (Continued)

Commodity	Type of Ship		MTON per Gang per Hour
General Cargo	C-2		31.2
	C-3		47.0
	C-4		47.0
	LASH	(Barges only)	50.0
	SEABEE		60.0
		Average	41.6
Ammunition	C-2		42.2
	C-3		48.2
	C-4		41.2
	LASH	(Barges only)	50.0
	SEABEE		60.0
		Average	44.2
Unit Equipment	C-2		67.5
	C-3		79.5
	C-4		72.0
	LASH	(Barges only)	50.0
	SEABEE		60.0
		Average	72.4
Reefer	C-2		34.0

NOTE: Additional Information
1. Add 2 days for sheathing ammunition ships.
2. Two cranes used to load containerships.
3. Five gangs used to load the three types of ships.
4. Loading based on a 16-hour day.
5. Shiploading based on experience.
6. Includes 1/2 day for opening and closing hatches and spotting booms.
7. Includes 1/2 day for shoring and dunnage.

FROM CONUS EAST AND GULF COASTS TO NORTHERN EUROPE

(TOTAL PORT AND TERMINAL HOLD TIME = AVERAGE TERMINAL PROCESSING PLUS SHIPLOADING TIME)

Type of Shipping	PEACETIME SUPPORT (8-Hour Shift - 5-Day Wk)			CONTINGENCY SUPPORT (16-Hour Shift - 7-Day Wk)		
	Avg Time in Tml (Days)	Shipload Time (Days)	Total Port/Tml Time (Days)	Avg Time in Tml (Days)	Shipload Time (Days)	Total Port/Tml Time (Days)
1. Containerized Cargo						
a. MTMTS-Stuffed	10	2	12	5	1 1/2	6 1/2
b. Source-Stuffed	4	2	6	2	1 1/2	3 1/2
2. Break-Bulk - Gen Cargo (Avg C-2, -3, and -4)	10	8	18	5	4	9
3. Ammunition (Avg C-2, -3, and -4)	4	8	12	2	4	6
4. RORO (GTS Adm. Wm. M. Callaghan only)	12	2	14	6	1 1/2	7 1/2
5. Unit Equipment (Avg C-2, -3, and -4)	NVAL	NVAL	NVAL	1	3 1/2	4 1/2

NOTE: MTMTS-stuffed container factors can be used for LASH or SEABEE barges pending development of usage data.

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WEST COAST

Commodity	Type of Ship		MTON Capacity	Days to Load
General Cargo	C-2		7,500	4.7
	C-3		11,500	5.7
	C-4		12,500	5.2
	LASH	(Barges only)	350	1 1/4
	SEABEE		850	1 1/2
Ammunition	C-2		6,000	4.4
	C-3		10,000	7.3
	C-4		11,000	8.1
	LASH	(Barges only)	350	1 1/4
	SEABEE		850	1 1/2
Reefer	C-2		5,500	4.6
Containers	Containership		24,000	1 1/4
Unit Equipment	C-2		8,000	3.5
	C-3		11,000	5.0
	C-4		13,000	5.0
	LASH	(Barges only)	350	2 1/4
	SEABEE		850	1 1/2

Commodity	Type of Ship		MTON per Gang per Hour
General Cargo	C-2		20
	C-3		25
	C-4		30
	LASH	(Barges only)	50
	SEABEE		60
Ammunition	C-2		17
	C-3		17
	C-4		17
	LASH	(Barges only)	50
	SEABEE		

WEST COAST (Continued)

Number MTON Per Gang Per Hour

Commodity	Type of Ship	MTON per Gang per Hour
Unit Equipment	C-2	50
	C-3	65
	C-4	75
	LASH (Barges only)	50
	SEABEE (Barges only)	60

NOTE: Additional Information:
1. Add 2 days for sheathing ammunition ships.
2. Two cranes used to load containerships.
3. Five gangs used to load the three types of ships.
4. Loading based on 16-hour day.
5. Shiploading based on experience.
6. Includes 1/2 day for opening and closing hatches and spotting booms.
7. Includes 1/2 day for shoring and dunnage.
8. LASH and/or SEABEE Barges only - total ship capacity: LASH - 27,010 MTON.
   SEABEE - 32,300 MTON.

APPENDIX B

VESSEL CHARACTERISTICS

TABLE IV
US FLAG BREAK-BULK FLEET CHARACTERISTICS, 31 MARCH 1975 (EXCLUDING MSC AND NDRF)

Class	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	Bale Cube a/ (MTON)	Deck Loaded 20-Ft Containers	Boom Capacity (LTON)
C4-S-58a	6	572	75	31	15,570	NVAL	60
C4-S-1u	6	565	76	32	16,825	167	60
C4-S-1a	6	564	76	32	18,400	NVAL	60
C4-S-1f	3	564	76	32	15,825	92	60
C4-S-1h	3	564	76	31	15,800	227	60
C4-S-1p	3	564	76	30	17,500	227	60
C4-S-1t	2	563	76	32	14,525	81	60 b/
C4-S-57a	11	561	75	32	16,075	128	70
C4-S-60a	6 c/	551	75	31	15,380	295	75
C4-S-64a	2	544	75	32	17,125	110	70 b/
C4-S-66a	12	540	76	33	18,750	138	160 b/
Ex-C4	5	523	72	33	19,725	NVAL	50 d/
Ex-C4	2	523	72	33	19,000	NVAL	70
Ex-C4	2	523	72	33	18,450	NVAL	50
Ex-C4	4	523	72	33	18,400	NVAL	25 e/
Ex-C4	2	523	72	32	16,550	NVAL	240 b/
C3-S-76a	5	522	70	31	15,075	N/A	75
C3-S-43a	3	506	70	31	15,800	N/A	60
C3-S-37c	8	495	69	32	14,125 f/	138	60
C3-S-37d	5	495	69	30	13,650	146	60
C3-S-46a	8	493	73	31	17,270	132 g/	60
C3-S-38a	4	493	73	28	13,800	108 h/	50
C3-S-A2	3	492	70	29	16,975	NVAL	30
C3-S-33a	8	488	68	31	10,625 to 12,000	N/A	60/75
C3-S-A3	2	473	66	28	12,575	NVAL	25
C2-S-B1	1	459	63	28	13,525	NVAL	30
C2-S-AJ5	1	459	63	28	11,200	NVAL	50

a/ Dry cargo only.
b/ With married fall.
c/ Two ships are presently under conversion to C6-S-60a, partial containerships.
d/ Two ships with 70-LTON booms.
e/ Two ships with 35-LTON booms.
f/ Four ships with 13,800 MTON.
g/ Four ships can be converted to partial containerships with 440 to 468 20-ft containers; as breakbulk, they can carry 247 20-ft containers.
h/ Plus 12 40-ft containers.

APPENDIX B

VESSEL CHARACTERISTICS

TABLE IV
US FLAG BREAK-BULK FLEET CHARACTERISTICS, 31 MARCH 1975 (EXCLUDING MSC AND NDRF)

Class	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	Bale Cube[a] (MTON)	Deck Loaded 20-Ft Containers	Boom Capacity (LTON)
C4-S-58a	6	572	75	31	15,570	NVAL	60
C4-S-1u	6	565	76	32	16,825	167	60
C4-S-1a	6	564	76	32	18,400	NVAL	60
C4-S-1f	3	564	76	32	15,825	92	60
C4-S-1h	3	564	76	31	15,800	227	60
C4-S-1p	3	564	76	30	17,500	227	60
C4-S-1t	2	563	76	32	14,525	81	60[b]
C4-S-57a	11	561	75	32	16,075	128	70
C4-S-60a	6[c]	551	75	31	15,380	295	75
C4-S-64a	2	544	75	32	17,125	110	70
C4-S-66a	12	540	76	33	18,750	138	160[b]
Ex-C4	5	523	72	33	19,725	NVAL	50[d]
Ex-C4	2	523	72	33	19,000	NVAL	70
Ex-C4	2	523	72	33	18,450	NVAL	50
Ex-C4	4	523	72	33	18,400	NVAL	25[e]
Ex-C4	2	523	72	32	16,550	NVAL	240[b]
C3-S-76a	5	522	70	31	15,075	N/A	75
C3-S-43a	3	506	70	31	15,800	N/A	60
C3-S-37c	8	495	69	32	14,125[f]	138	60
C3-S-37d	5	495	69	30	13,650	146	60
C3-S-46a	8	493	73	31	17,270	132[g]	60
C3-S-38a	4	493	73	28	13,800	108[h]	50
C3-S-A2	3	492	70	29	16,975	NVAL	30
C3-S-33a	8	488	68	31	10,625 to 12,000	N/A	60/75
C3-S-A3	2	473	66	28	12,575	NVAL	25
C2-S-B1	1	459	63	28	13,525	NVAL	30
C2-S-AJ5	1	459	63	28	11,200	NVAL	50

[a] Dry cargo only.

[b] With married fall.

[c] Two ships are presently under conversion to C6-S-60a, partial containerships.

[d] Two ships with 70-LTON booms.

[e] Two ships with 35-LTON booms.

[f] Four ships with 13,800 MTON.

[g] Four ships can be converted to partial containerships with 440 to 468 20-ft containers; as breakbulk, they can carry 247 20-ft containers.

[h] Plus 12 40-ft containers.

TABLE V
US CONTAINERSHIP FLEET CHARACTERISTICS
31 March 1975

Class	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	No. of Containers[a]			Lift Capacity (LTON)
					20-Ft	40-Ft	Other	
SL-7	8	947	105	35	NVAL	200	896[b]	NVAL
SL-18	2	721	95	34	NVAL	321	412[b]	9
C7-S-88a	2	721	95	34	NVAL	360	280[b]	NVAI
	2	721	95	34	NVAL	0	1,174[c]	NVAL
C7-S-68	2	705	90	33	592	326	NVAL	NVAL
C7-S-68e	6	701	90	32	766	224	NVAL	NVAL
*C4-J1	2	685	78	30	NVAL	NVAL	622[b]	NVAL
*C4-J	4	685	78	30	NVAL	NVAL	609[b]	NVAL
*C4-JC	3	685	78	30	NVAL	NVAL	602[b]	27
C6-S-85a	4	668	90	33	1,098	0	NVAL	NVAL
C6-S-85b	4	668	90	33	792	196	NVAL	NVAL
*C6-S-1xa	4	668	76	33	356	296	NVAL	NVAL
*C6-S-69c	5	668	82	31	680	103	NVAL	NVAL
*EX-C4	4	633	72	29	NVAL	482	NVAL	NVAL
*	2	630	72	32	NVAL	0	805[c]	NVAL
*T3-J	4	627	78	27	NVAL	NVAL	476[b]	25
C5-S-736	6	610	78	32	916	0	NVAL	NVAL
*T2-M	3	524	68	30	NVAL	NVAL	332[b]	NVAL
*EX-T2e	3	524	75	30	N/A	N/A	N/A	NVAL
*T2	1	524	68	30	NVAL	NVAL	196[b]	25
*C4-X	1	523	72	30	NVAL	NVAL	325[b]	NVAL
*C4-X2	8	523	72	31	NVAL	NVAL	360[b]	NVAL
*EX-C4	2	523	72	33	470	NVAL	NVAL[d]	5
*C2-L	2	504	74	25	NVAL	NVAL	274[b]	22
*C4-M	2	497	72	30	NVAL	NVAL	354[b]	NVAL
*T2-M	1	497	72	30	NVAL	NVAL	348[b]	NVAL
*EX-C3	1	492	70	29	NVAL	NVAL	488[c]	NVAL
*C2-X	4	469	63	28	NVAL	NVAL	225[c]	NVAL
*C2-C	6	469	72	25	NVAL	NVAL	226[c]	26
	1	338	32	18	NVAL	NVAL	212[d]	25

a/ Capacity expressed with maximum 20-foot container configuration.
b/ 35- x 8- x 8-1/2-ft container.
c/ 24- x 8- x 8-1/2-ft container.
d/ Also carries 25 automobiles.
*Conversions

TABLE VI
US BARGE-SHIP FLEET CHARACTERISTICS, 31 MARCH 1975

Class and Design	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	No. of Barges	No. of Containers*	Lift Capacity (LTON)
C9-S-81d LASH	3	893	100	38	85	24 20-ft; 24 40-ft	510
C9-S-81d LASH	6	893	100	38	89	0	446
C8-S-82a SEABEE	3	876	106	39	38	160 40-ft	2,000
C8-S-81b LASH	11	820	100	35	49	114 20-ft	450

*Design configuration; other configurations possible.

TABLE VII
US ROLL-ON/ROLL-OFF FLEET CHARACTERISTICS, 31 MARCH 1975

Design	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	Cargo Load Area (Sq Ft)	Boom Capacity (LTON)	Min Deck Clearance
USNS Comet	1	499	78	27	96,704	60	6 ft 11 in.
USNS Sealift	1	540	83	29	99,030	70	8 ft 6 in.
Adm. Wm. M. Callaghan	1	694	92	29	165,000	240[a]	9 ft 4 in.
Ponce de Leon	7[b]	700	92	28	167,167[c]	NVAL	5 ft 9 in.
Maine	4[d]	648	102	34	159,442	15	9 ft 11 in.

[a] Married fall.
[b] One vessel under construction.
[c] One ship with 189,942 sq ft.
[d] Under construction.

TABLE VIII
US FLAG PARTIAL CONTAINERSHIP FLEET CHARACTERISTICS, 31 MARCH 1975 (EXCLUDING MSC AND NDRF)

Class	No. of Ships	Overall Length (Ft)	Breadth (Ft)	Max Draft (Ft)	No. of Containers[a] 20-Ft	No. of Containers[a] 40-Ft	Bale Cube[b] (MTON)	Boom Capacity (LTON)
C6-S-1qc	3	663	76	33	521	82	6,900	60
C5-S-75a	5	605	82	35	400[c]	NVAL	27,050	70
C5-S-37e/f	13	592	69	32	94	30	16,530	60
C4-S-69b	5	579	82	33	216[c]	0	19,610	60
C4-S-1q	2	564	76	32	468[c]	NVAL	13,300	30[d]
C4-S-65a	6	560	81	30	138[c]	NVAL	11,800	80[d]
C4-S-49a	4	547	79	29	175	0	9,150[e]	40[e]
C4-S-64a	5	544	75	32	232	NVAL	8,810	30[f]

[a] Dry cargo only.
[b] Capacity expressed with maximum 20 ft container configuration.
[c] Using a hold stowage system.
[d] Have onboard gantry crane.
[e] Carries 12 passengers.
[f] Ships with 70 LTON boom.

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MTMC Report TE 73-44		

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Port Capacity; Cargo Throughput; Throughput Analysis; Port Methodology; Port Capability; Marine Terminals; Terminal Studies.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A methodology was developed for determining and predicting the cargo throughput capability of marine terminals. It systematizes the input factors into mathematical expressions with which one can manually calculate cargo throughput rates. The methodology enabled planners and engineers to estimate marine terminal capability (port capacity) for four types of cargo: break-bulk, containerized, roll-on/roll-off, and LASH/SEABEE barges. The procedure used for estimating capability is the weak-link analysis, in which each basic

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subsystem in a port is analyzed separately to determine its cargo throughput capability. The subsystem having the least capability is the weak link, and the output of the port system as a whole can be no greater than that of this weak link. Example problems are shown, with detailed calculations, for marine terminal operations with the four different types of cargo mentioned above. Also, an example is shown wherein analysis is made of combined operations. The developed procedure is applicable either for loading ships in CONUS or for unloading ships at overseas ports.